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AN ASSESSMENT OF THE RISKS PRESENTED BY THE USE
OF CARBON FIBER COMPOSITES IN COMMERCIAL AVIATION

VOLUME I: FINAL REPORT

VOLUME II: SUPPORTING APPENDICES

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PHASE I

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Volume I: Final Report

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1. EXECUTIVE SUMMARY

1.1 INTRODUCTION

Carbon fiber (CF) composites are being used to an increasing extent in commercial aircraft, due to their excellent structural properties. Since carbon fibers are highly conductive, a potential risk has been identified in the event that an aircraft with CF composite structures is involved in an accidental fire. If carbon fibers are released from the fire, they could disperse in the atmosphere and eventually cause damaging short circuits in electronic equipment at remote locations. This phenomenon could conceivably result in economic losses ranging from repair of failed equipment to interruption of business operations, and could affect many segments of society. The purpose of this study was to assess the risks presented to the nation as a whole by the use of CF composites in commercial aircraft, in terms of the potential economic losses from air carrier accidents.

To support the investigation, experimental data from a number of different sources were used, including tests of CF release from burning composites and vulnerability tests for selected equipment. Field surveys were conducted in the vicinity of several major airports in order to characterize the types of facilities that might be exposed to carbon fiber releases. Census data were employed to enumerate the numbers of residential and commercial establishments in the vicinity of the 26 large hub airports identified by the Federal Aviation Administration. These data formed part of the input to a risk simulation model, which produced a "conditional risk profile", showing the probability of different amounts of loss given that an accidental release of CF has occurred. Finally, a national risk profile was developed, which estimates the annual losses due to CF usage in commercial aircraft based upon the anticipated usage in 1993. These results are presented in Section 1.4 below.

Many of the input parameters that entered into this risk assessment were based upon existing data, and are subject to future refinement as a result of programs currently being sponsored by NASA and other organi-

zations. In addition, the approach used to estimate risks involved a number of assumptions, which were necessary either because the events and processes involved were not fully understood, or because it was not possible to model them in sufficiently fine detail within the scope of this study. Hence, the risk profiles that were generated have some uncertainty attached to them. The overall intent was to develop conservative risk estimates which would overstate rather than understate the risk, and to provide quantitative results which were useful for decision-making given our current state of knowledge. Application of the present methodology to an enhanced set of inputs will produce an improved risk assessment.

1.2 GENERAL APPROACH

1.2.1 Objectives

The objectives of this study may be summarized as follows:

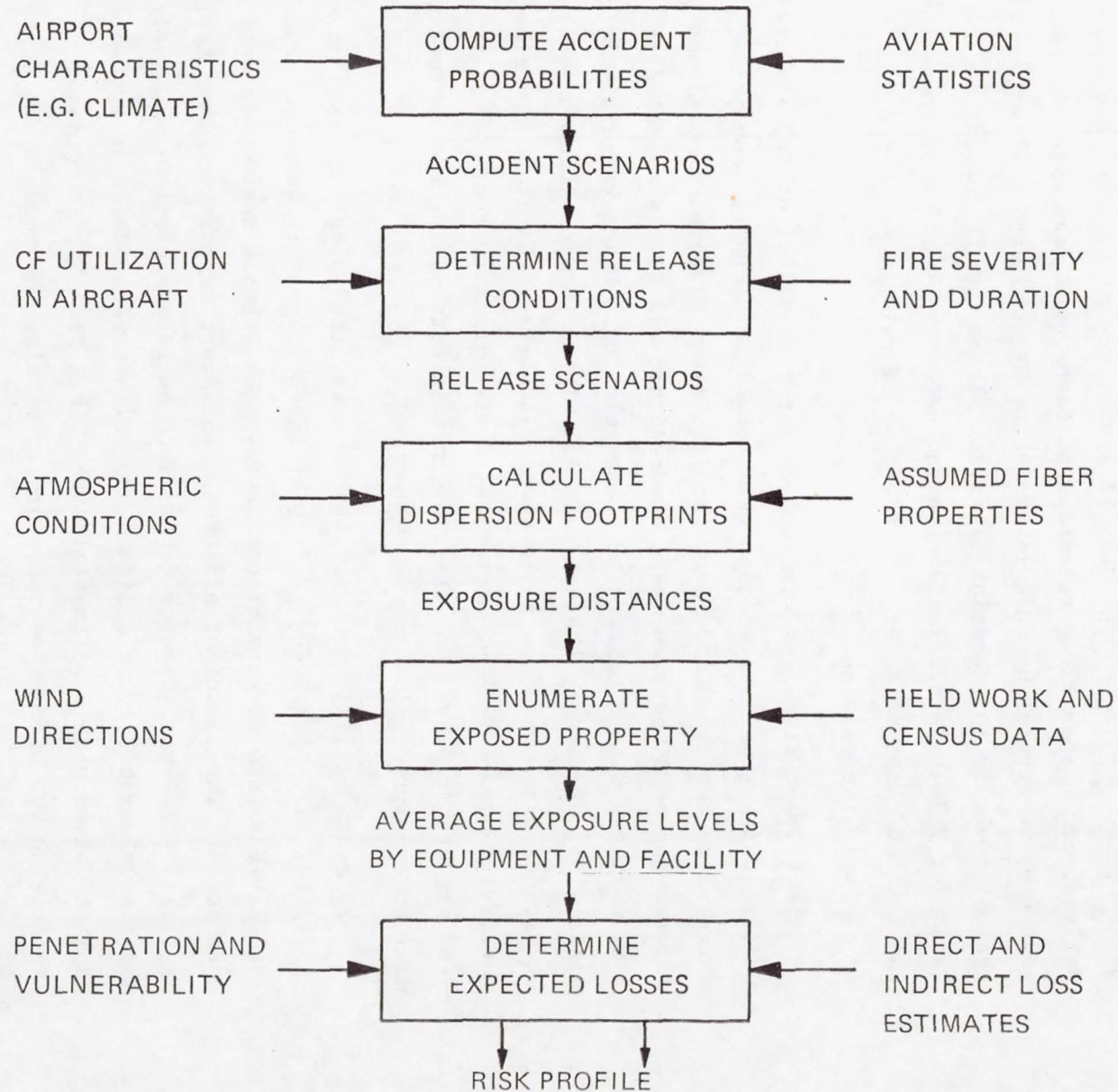
- To project the utilization of CF composites in commercial aircraft from the present until 1993.
- To estimate the probability and magnitude of CF release from accidental fires during normal air carrier operations.
- To analyze the possible dispersion of fibers due to a fire or a fire with a delayed explosion, and their penetration of surrounding structures.
- To quantify the economic losses that might result from fibers making contact with electronic equipment and inducing failures.

1.2.2 Methodology

To satisfy the above objectives, a methodology was developed which analyzes the entire sequence of relevant physical events and then simulates these events repeatedly to obtain a probability distribution of the resulting losses. The methodology may be understood by referring to Figure 1-1.

FIGURE 1-1

OVERVIEW OF RISK ANALYSIS METHODOLOGY



The specific airports selected for detailed analysis were the 26 large hubs which account for a majority of air traffic in the U.S. Using aviation statistics in conjunction with airport characteristics, the probability of an accident with fire involving a commercial jet aircraft was computed for each large hub. A finite set of accident scenarios were derived, and carbon fiber release conditions were developed for each scenario, incorporating information about CF composite utilization and typical severity and duration of fires. These conditions formed the basis for release scenarios, which included the location of the accident, the total CF mass released, and the type of release - either a fire plume or an explosive release.

The release scenarios were fed as input to either of two dispersion models, which took into account the probable atmospheric conditions surrounding the accident. Both the fire plume dispersion model and the fire-explosion dispersion model assumed that all CF was released as single fibers with a uniform settling velocity. Using Pasquill-Gifford dispersion parameters, these models calculated the resulting exposure at various distances from the accident locations. Exposure distributions were determined within 40 sectors of a circular grid centered at the airport. Wind directions played an important role in determining the sectors with maximum exposure.

By means of field work and census data, the potentially vulnerable facilities were enumerated in each of these geographic sectors. Facilities were divided into industrial categories, and private residences were also considered. The amount of electronic equipment exposed was then estimated by facility. Penetration of fibers into building interiors was analyzed, and the vulnerability of equipment to failure was modeled in probabilistic fashion, based upon experimental data. This permitted computation of the expected number of equipment failures. Finally, by means of an economic analysis of various possible losses, the total dollar damage resulting from CF exposure was estimated.

The simulation model generated a risk profile by repeatedly and randomly selecting accident scenarios and determining the resulting losses.

This was done for each large hub, and then the 26 risk profiles were extrapolated to yield a national risk profile, which also incorporated the risk from cruise accidents between airports. Numerical details of the input data developed for the simulation and of the final results are provided in Sections 1.3 and 1.4.

1.2.3 Important Assumptions

A number of assumptions were incorporated into the risk analysis. These were necessary either because precise information was not available in certain areas, or because the scope of the study did not permit elaboration of certain issues. The most important of these assumptions are listed below, and the anticipated effect of each one upon the resultant risk profile is indicated. These effects fall into three categories: Conservative, implying an overestimation of risk; non-conservative, implying an underestimation of risk; and unclear, implying that no definite effect upon the risk can be expected in either direction. Most of the assumptions that were adopted are conservative, but particularly in the area of economic loss estimation there may be additional costs which we were not able to quantify. Future investigations will focus upon validating or modifying some of these assumptions, and obtaining more detailed descriptions of economic impacts upon various facilities.

- If an aircraft carries composite, and a fire occurs, the composite will always be involved.

Effect: Conservative. Portions of the aircraft containing CF may not be damaged by fire.

- Explosive releases of CF are possible, in which up to 25% of the CF mass can be released almost instantaneously.

Effect: Conservative. It has not yet been demonstrated that fuel deflagrations in aircraft fires will produce this phenomenon.

- All CF released from a fire is in the form of single fibers.
Effect: Conservative. Single fibers will disperse farthest, and have the greatest potential for penetrating to equipment. (The one possible exception is the vulnerability of power stations to clumps of fibers.)
- Atmospheric conditions remain constant during dispersion of the carbon fiber cloud.
Effect: Unclear. Though weather will fluctuate, the net effect on dispersion should average out over many simulation trials.
- The presence of precipitation is ignored in the dispersion analysis.
Effect: Conservative. Precipitation would tend to wash out airborne fibers and reduce downwind exposures.
- Within a facility category, all facilities are assumed to be similar in terms of penetration properties and economic characteristics.
Effect: Unclear. Considerable variations will exist among facilities, but these will average out when losses are aggregated over a large area.
- Equipment is assumed to be in an activated state during exposure.
Effect: Conservative. Reactivation of equipment after exposure may produce failures, but vulnerability in such a case is most probably reduced.
- If a unit of critical equipment fails, the facility is shut down.
Effect: Conservative. The presence of redundancies or backup equipment may minimize economic loss.

- Secondary impacts of business interruption are not included in the economic loss estimate.

Effect: Non-conservative. The shutdown of one facility may have subsequent impact upon other sectors of business or society at large (e.g., mass transit, telephone system).

- The amount of vulnerable electronic equipment is assumed to remain at current levels.

Effect: Non-conservative. Rapid growth is expected in the electronics industry during the next decade.

- Costs associated with decontamination and precautionary procedures are not incorporated.

Effect: Non-conservative. The cost of anticipating failures due to CF release or of preventing additional failures subsequent to a release may be significant, especially at vital installations such as airports.

1.3 ANALYSIS OF DAMAGE SCENARIOS

1.3.1 Carbon Fiber Markets

The first objective of the study was to investigate the market for fiber composites from the present day until 1993. There are several types of carbon fiber composites being produced, but they all consist of fine carbon filaments bound into an epoxy matrix. (Fibers can be released accidentally only if this matrix is buried away.) The producers and users of carbon fibers were identified, and market growth was forecast for sporting goods, aerospace, and the industrial sector. The overall projected growth rate for CF usage was 25% to 30% per year. For commercial air carriers, the applications of CF are expected to be restricted to jet aircraft, so the subsequent accident probability analysis ignored other aircraft. CF usage was also examined for both general aviation and helicopters, but these were not included in the scope of the risk assessment. According to estimates furnished by NASA, in 1993 approximately 50% of the domestic jet fleet will carry carbon fibers, with average CF weight per aircraft ranging from about 500 kg to about 2000 kg depending

on the aircraft size. These were comparable to predictions developed independently by Arthur D. Little, Inc. The NASA projections, which were used as inputs to the risk simulation, are displayed in Table 1-1.

1.3.2 Accident Probability Estimates

The frequency and nature of domestic air carrier accidents were examined through a detailed analysis of National Transportation Safety Board records. A data base was constructed for all accidents or incidents from the years 1968 through 1976, and attention was focused upon those accidents involving total destruction or substantial damage of jet aircraft, along with fire or explosion. Through a statistical analysis of the data, probability distributions were derived for a number of variables which characterize an accident scenario, including the weather conditions, the phase of operation, and the location of the accident. Accidents involving only fire were distinguished from those in which a fire was followed by a delayed explosion, caused by rapid deflagration of fuel. The present incidence of accidents with fire for jet operations was found to be approximately 5 per year. Taking into account the growth of air traffic and the projected CF usage, 3.2 accidents per year are predicted in 1993 with a potential for CF release.

The results of the accident probability analysis are highlighted in Table 1-2, which shows the expected frequency of incidents or accidents under different weather conditions, and in Table 1-3, which shows the likelihood of various accident characteristics given that an accident occurs. Instrument Flight Rules (IFR) weather corresponds to poor ceiling and visibility, and accidents are much more likely under these conditions. Table 1-4 shows the estimated proportion of accidents or incidents which occur on-airport. In the full analysis, the actual spatial location of an accident relative to the runway was simulated, taking into account the orientation and usage of the runways for each hub airport.

TABLE 1-1

FLEET MIX AND AMOUNT OF CARBON FIBER USED
(As per NASA/AC Companies' Projection)

	1985			1993		
	<u>% of Total</u>	<u>% Carrying Fiber</u>	<u>Wt. of CF per Aircraft (kg)</u>	<u>% of Total</u>	<u>% Carrying Fiber</u>	<u>Wt. of CF per Aircraft (kg)</u>
Small	25	20	100	25	50	500
Medium	60	20	150	60	60	700
Large	15	33	500	15	50	2000

TABLE 1-2: EXPECTED FREQUENCY OF JET AIRCRAFT ACCIDENTS WITH FIRE

(Based on 1968-1976 Data)

	FREQUENCY PER 10 MILLION OPERATIONS		
	<u>IFR WEATHER (11%)</u>	<u>VFR WEATHER (89%)</u>	<u>OVERALL</u>
Cruise	2	1	1
Static, Takeoff, or Landing	24	3	5.2
All Phases	26	4	6.2

TABLE 1-3: CONDITIONAL PROBABILITY OF PHASE OF OPERATION AND SEVERITY OF DAMAGE FOR JET ACCIDENTS WITH FIRE

(Based on 1968-1976 Data)

	<u>TOTAL DESTRUCTION</u>	<u>SUBSTANTIAL DAMAGE</u>
Take-off	0.16	0.09
Landing	0.38	0.07
Cruise	0.11	0.05
Static or Taxi	0.04	0.10

TABLE 1-4: CONDITIONAL PROBABILITY OF LOCATION OF ACCIDENTS OR INCIDENTS BY OPERATIONAL PHASE AND SEVERITY OF DAMAGE

(Based on 1968-1976 Data)

		<u>ON-AIRPORT</u>	<u>OFF-AIRPORT</u>
Substantial Damage	All Phases	0.88	0.12
Total Destruction	Take-off	0.75	0.25
	Landing	0.55	0.45

1.3.3 Carbon Fiber Release and Dispersion

Assuming that an accident of a given type had occurred, a release scenario was constructed to describe the intensity of the fire and the resulting amount of carbon fibers released. These release scenarios were based upon information about the amount of fuel on board and the effect of fire-fighting activities. Table 1-5 lists some of the assumed release conditions. In addition, the probable weather conditions at the time of the accident were drawn from climate statistics on temperature, wind, and atmospheric stability class for the 26 large hub airports. Precipitation data were included in the weather scenarios, but the dispersion model described below conservatively assumed that no precipitation would occur. It was found, however, that accidents with fire are likely to be accompanied by rain.

The release conditions were fed as input into a dispersion analysis, which computed the CF exposure at any point relative to the location of the release. Two alternative dispersion models were utilized, corresponding to two different release scenarios - a fire with a delayed explosion, and a fire plume. The fire-explosion model assumed an instantaneous release of the CF mass, while the tilted plume model assumed a continuous release during the period of burn. Both models used a modified Gaussian approach, with Pasquill dispersion parameters, and incorporated a particle settling velocity. The assumption was made that all particles released were single fibers. Some typical outputs of the fire plume model are shown in Table 1-6, for varying release conditions. Exposure is the time integral of concentration, and is measured in decades; thus, the 10^5 exposure contour corresponds to all geographic locations which experienced an exposure of at least 10^5 fiber-seconds per cubic meter. As a result of multiple dispersion calculations under a variety of release conditions, it was found that the exposures predicted by the fire-explosion model reached higher levels, but that the exposure contours from the fire plume model covered much larger areas, often in excess of 100 km.².

TABLE 1-5
RELEASE SCENARIO ASSUMPTIONS

Accident/Incident Description	Percent of Carbon Fibers Released		Percent of Fuel Burned*	Duration*
	Fire	Fire and Explosion		
On Airport Total Destruction	10%	25%	33%	4 min.
Off Airport Total Destruction	20%	25%	100%	30 min.
On Airport Substantial Damage	5%	10%	6.7%	4 min.
Off Airport Substantial Damage	10% 1	10%	20%	12 min.

* Source: ALPA, Massport

TABLE 1-6

SAMPLE OUTPUT FROM FIRE PLUME MODEL

Scenario: 500 KG of Carbon Fibers Released Over a 10-Minute Period

EXPOSURE LEVEL	CONTOUR DIMENSIONS (M.)	NEUTRAL ATMOSPHERE 4M./SEC. WIND VELOCITY	MODERATELY STABLE ATMOSPHERE 2M./SEC. WIND VELOCITY
10^5 FIBER-SEC/M ³	NEAREST DISTANCE	0	39,150
	FARTHEST DISTANCE	0	57,150
	MAXIMUM WIDTH	0	4,247
	AREA (KM ²)	0	60
10^3 FIBER-SEC/M ³	NEAREST DISTANCE	6,300	28,150
	FARTHEST DISTANCE	94,300	63,150
	MAXIMUM WIDTH	16,107	8,363
	AREA (KM ²)	1,110	230

1.3.4 Building Penetration

The next step in the sequence of physical events that were studied is the penetration of fibers into the interiors of structures. Based on the external exposure computed by the dispersion model, the internal exposure for different types of facilities was calculated using a multiplicative transfer rate. To determine transfer functions, a detailed analysis of building penetration was performed. This analysis incorporated such variables as window openings, filter efficiencies, and ventilation rates into a building penetration model. By applying the model to specific building characteristics derived from field surveys, appropriate ranges of values were derived for the transfer functions corresponding to a wide variety of buildings and structures, including aircraft. Table 1-7 shows some selected types of facilities and the corresponding ranges of transfer function values that were computed. The results indicated a large variability in the penetration potential of different buildings, even for facilities within the same industrial classification. Part of the variability is due to uncertainty about the physical parameters affecting penetration, and part is due to the non-uniformity of construction and maintenance practices.

1.3.5 Equipment Vulnerability

Provided that the carbon fibers can actually penetrate structures to create sufficiently high interior exposures, they are capable of damaging many types of equipment. The class of equipment most vulnerable to carbon fibers appears to be low-voltage electronic microcircuitry but motor generators and transformers may also be vulnerable. Estimates of the mean exposures at which various types of equipment would fail were derived from the existing experimental data. The mechanisms of damage were identified, and the possible effects of different sizes of particles were described. For risk analysis purposes, the exponential failure model shown in Figure 1-2 was used to determine the failure probability of a unit of equipment at different levels of exposure.

Due to the inadequacy of available experimental data, some uncertainty remains about the possibility of equipment failure subsequent to

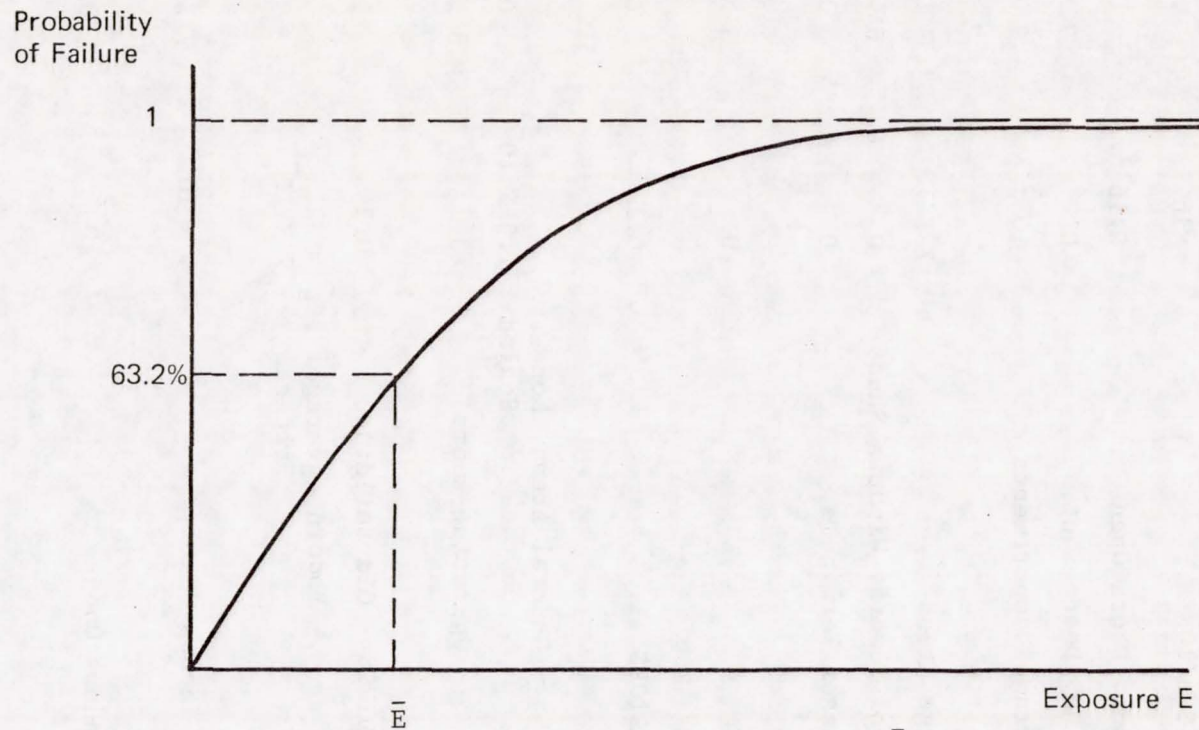
TABLE 1-7

AIRBORNE EXPOSURE TRANSFER FUNCTION
OVERVIEW OF RESULTS

AREA DESIGNATION	AETF Range	
	Min.	Max.
AIRCRAFT - Cabins, Doors Open	0.16	0.68
- Cabins, Doors Shut	0	9×10^{-3}
- External Compartments	10^{-3}	9×10^{-2}
AIRPORT - Baggage Areas	7×10^{-2}	0.87
- Control Towers, Windows Shut	0	6×10^{-3}
- Passenger Terminals	0	10^{-3}
COMPUTER ROOMS	0	3×10^{-3}
EMERGENCY GENERATORS	0.1	0.7
HEALTH FACILITIES - General Areas, Non-Sealed	1.5×10^{-2}	0.44
- Operating Rooms	0	3×10^{-4}
INDUSTRIAL BUILDINGS - Old Building	0.3	0.7
- Modern, Average Filters	7×10^{-5}	0.13
OFFICE AREAS - Windows Shut	4×10^{-4}	7×10^{-2}
RESIDENCES - Windows Open	10^{-2}	0.7

FIGURE 1-2

ELECTRONIC EQUIPMENT FAILURE MODEL



$$\text{Probability of Failure} = 1 - e^{-\frac{E}{\bar{E}}}$$

$\bar{E}$ = Mean Exposure for Failure

EXPOSURE	PERCENT FAILURES
$\bar{E} / 100$	1.0%
$\bar{E} / 10$	9.5%
$\bar{E}$	63.2%
$10 \bar{E}$	99.9%

exposure as a result of reactivation of the equipment. Therefore, it was assumed that exposed equipment would not fail as a result of reactivation. For failures immediately after exposure, estimates were made of the mean exposure that would induce failure in different classes of equipment, and these were used as the parameter $\bar{E}$ in the failure model. A selected list of these estimates is given in Table 1-8; the accompanying classification of failure impacts is described below.

1.3.6 Economic Loss Estimates

The final component of the damage scenario was the enumeration of exposed facilities and their potential losses. In view of the large distances over which the carbon fibers could disperse, the identification of potentially vulnerable facilities extended over an 80-kilometer radius from each large hub airport. This area was subdivided into a circular grid of forty sectors, and the numbers of establishments in each sector were estimated from census data. The categories of facilities that were considered are summarized in Table 1-9. Field visits were made to typical establishments in many of these categories, with emphasis placed upon those facilities which relied heavily on electronic equipment.

Assuming similarity among facilities within each category, the impacts of equipment failure upon the facility were classified as being either critical (business shutdown), disruptive (increased operating expenses), or minor (equipment costs only). The resulting economic losses were then estimated, including both equipment repair costs and business interruption costs. Secondary costs other than the direct consequences of a failure were not incorporated into the analysis. Given a set of exposure values resulting from a particular accident scenario, the total losses were computed on the basis of the expected number of failures in each facility category by geographic sector.

1.4 RISK ASSESSMENT RESULTS

1.4.1 Frequency of Losses

After the above analyses had been completed, the resulting estimates of CF use, accident frequency, CF release and dispersion, penetration,

TABLE 1-8

SELECTED VULNERABILITY ESTIMATES

Facility Category	Equipment Type	Failure Category	Mean Exposure (Fiber-Sec./M. ³)
HOUSEHOLDS	TV / STEREO	REPAIR	6.4×10^8
AIRPORT CONTROL TOWER	ATC CONSOLES	REPAIR	7×10^5
AIRPORT CONTROL TOWER	ATC COMPUTER	REPAIR	4.9×10^9
SHIPYARDS	CRANES	REPAIR	4.0×10^5
POST OFFICE	ELECTRONIC SORTERS	REPAIR	5.0×10^5
AIRPORT TERMINAL	CRT DISPLAYS	REPAIR	1.6×10^7
MANUFACTURERS	TELEPHONE PBX	DISRUPTIVE	7.0×10^5
AIRCRAFT	AVIONICS INSTRUMENTS	DISRUPTIVE	1.0×10^6
RADIO/TV STATION	CONTROL ROOM	CRITICAL	3.0×10^5
RETAIL OUTLETS	POINT OF SALE TERMINAL	DISRUPTIVE	1.0×10^7
BUSINESS SERVICES	GENERAL OFFICE EQUIP.	DISRUPTIVE	5.0×10^5
HOSPITALS	POWER GENERATOR	REPAIR	9.8×10^5
EDP SERVICES	COMPUTER	CRITICAL	4.9×10^9

TABLE 1-9

FACILITY CATEGORIES FOR ECONOMIC ANALYSIS

- 1 Households
- 2 Police Cars
- 3 Shipyards
- 4 Automobile Radios
- 5 Post Office (major sorting centers)
- 6 Subway, Railroad
- 7 Manufacturers of Power Transmission Equipment (SIC 3568)
- 8 Manufacturers of Electronic Computing Equipment (SIC 3573)
- 9 Telephone Company - Central Switching Facility
- 10 Telephone Companies - Branch Office (SIC 481)
- 11 Radio, Television, Communication Services (SIC 483, 489)
- 12 Gas and Electric Utilities (SIC 491, 492, 493)
- 13 General Merchandise Retailers (SIC 531, 56, 57, 59)
- 14 Retail Grocers (SIC 541)
- 15 Financial and Insurance Institutions (SIC 602, 612, 63)
- 16 Business Services (SIC 73, except 737, 7391)
- 17 Computer Programming, Software Services, Data Processing (SIC 737)
- 18 Electronic R&D Labs, Universities, Colleges (SIC 7391, 822)
- 19 Hospitals (SIC 806)
- 20 Airplanes at Airports
- 21 Airport Control Tower
- 22 Airport Terminals
- 23 ASR Field Radar at Airport
- 24 LOC at Airport
- 25 VOR at Airport

vulnerability, and economic loss were used as input to a Monte Carlo simulation model. This computerized model performed repeated simulations of random accidents at each of the 26 large hub airports, thus generating a set of airport risk profiles. The total losses from any single incident ranged from only a few thousand dollars to a maximum observed value of \$9 million. The simulation was run using 1993 CF utilization figures. Sensitivity analyses were performed to assess the relative importance of certain key variables, and CF mass released was found to have a strong effect on total loss.

The 26 airport risk profiles were combined and extrapolated to include all other airport operations as well as cruise accidents, and the result was a conditional probability distribution for the losses due to a single accident or incident occurring anywhere in the U.S. This distribution was multiplied by the accident frequency estimate of 3.2 per year, to obtain the 1993 "loss frequency curve" shown in Figure 1-3. The loss frequency curve shows the number of CF incidents per year which may be expected to result in losses exceeding a certain value. For example, an incident causing \$1 million or more damage will occur with a frequency of approximately 1/10 per year, or once every ten years.

1.4.2 National Risk Profile

The loss frequency curve shows the potential impact of a single incident, but does not provide an estimate of total annual losses due to CF releases from commercial aircraft fires. To accomplish the latter a convolution procedure was used, and the result was a probability distribution for the total losses incurred by one or more incidents during a year. This "national risk profile" for 1993 is shown in Figure 1-4, and shows the probability of annual losses exceeding various amounts. The mean annual losses in 1993 were predicted to be \$419,000, with a probability of less than 1% of exceeding \$9 million. The probability of exceeding \$1 million is approximately one in ten.

Based on the sensitivity analyses mentioned in Section 1.4.1, confidence bounds were estimated for the national risk profile, and these are shown by the vertical line segments in Figure 1-4. To obtain a

FIGURE 1-3

National Annual Loss Frequency, 1993
(Carbon Fiber Utilization in Commercial Aircraft in the U.S.)

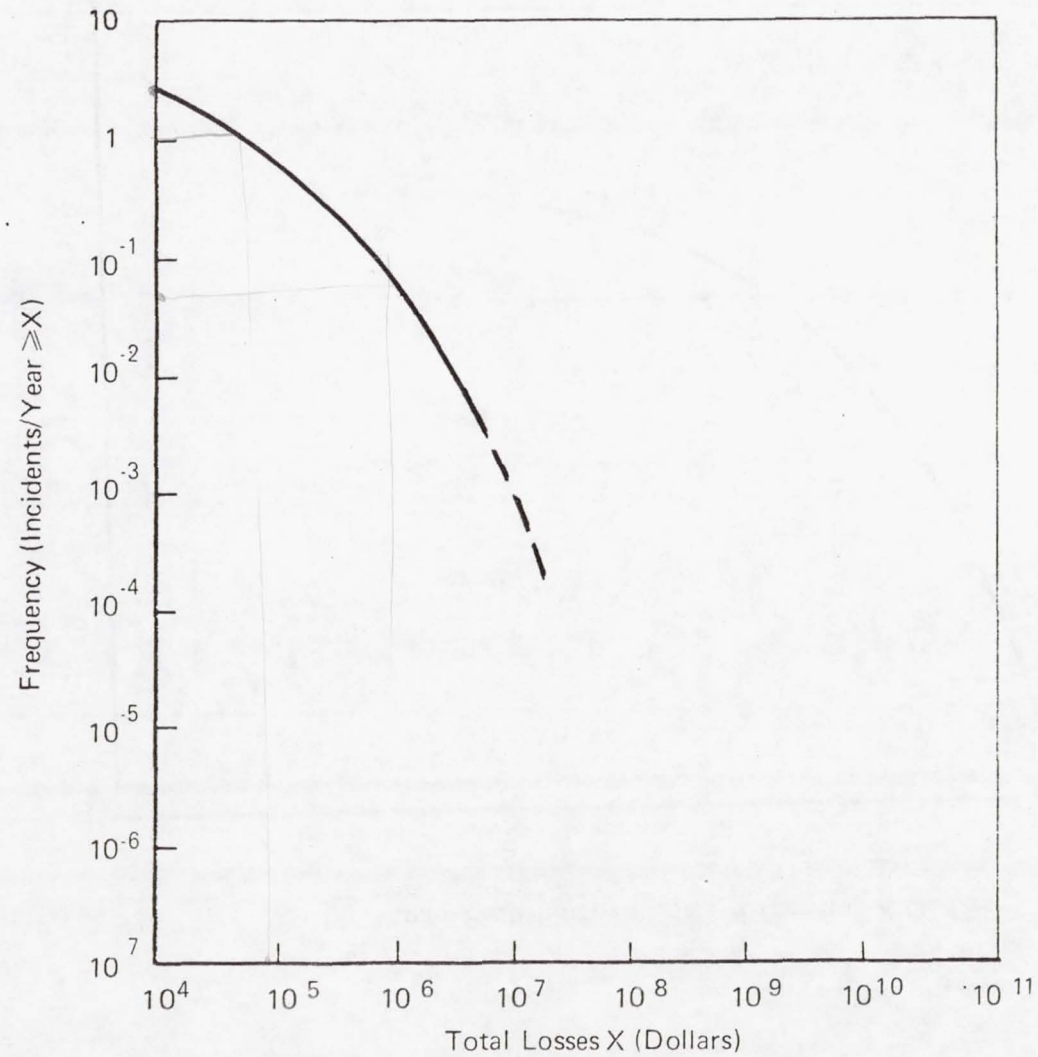
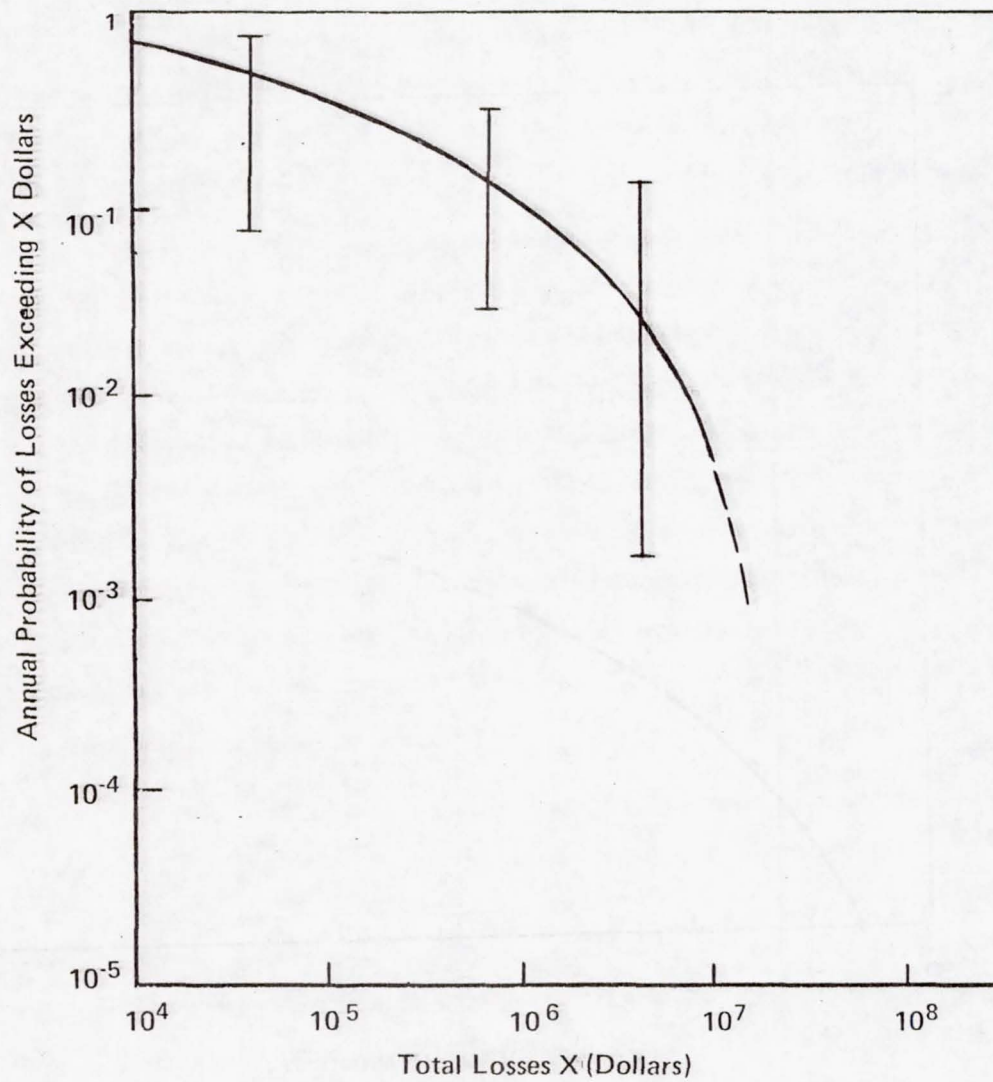


FIGURE 1-4

ANNUAL RISK PROFILE FOR
CARBON FIBER RELEASES FROM COMMERCIAL AIR CARRIERS
(1993 CF Utilization)



EXPECTED ANNUAL LOSS = \$419,000

national risk profile for 1985, simulation and extrapolation techniques were applied in a similar manner. In this case, the expected (i.e., mean) annual losses were only \$51,000, and the probability of exceeding \$1 million was about 1%.

1.5 CONCLUSIONS

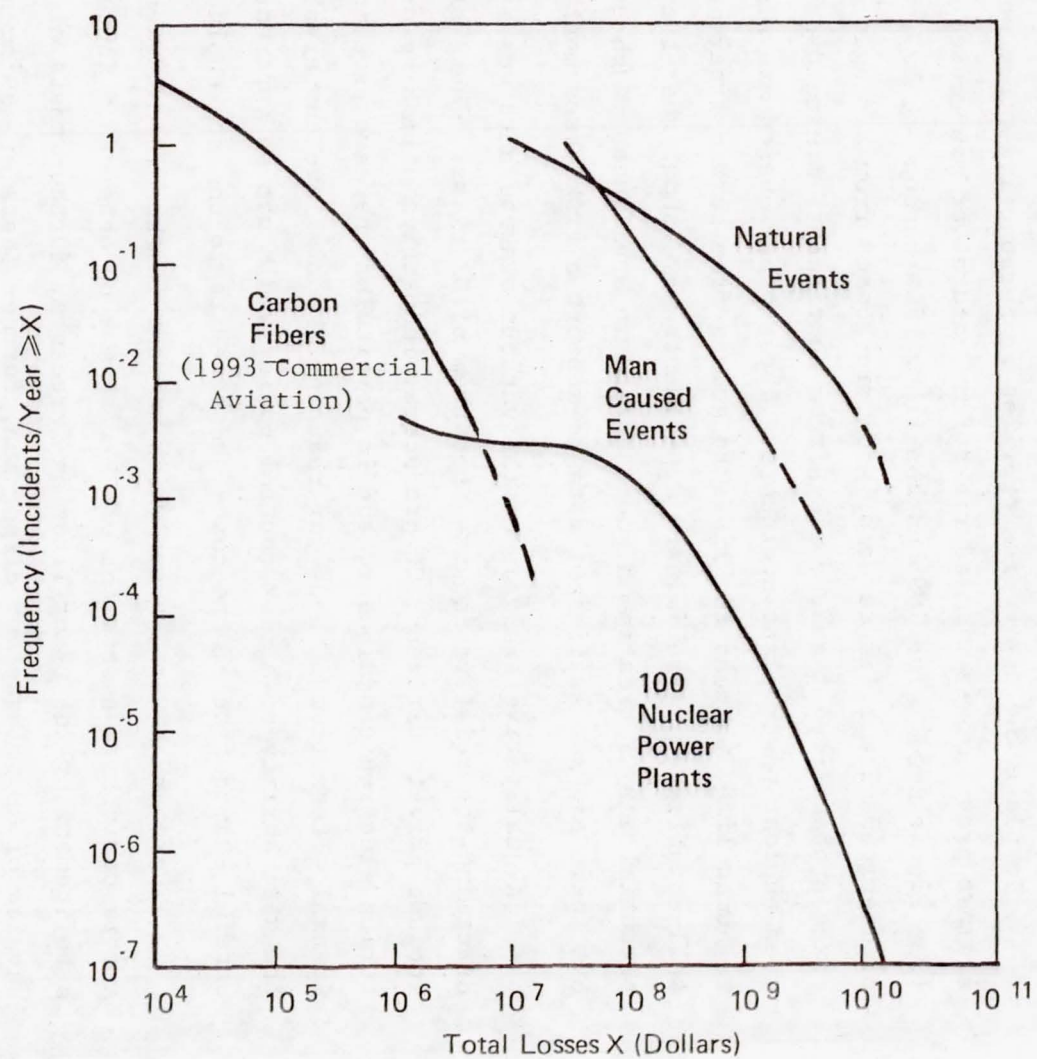
To place the above risk profiles in perspective, they were compared against previously-estimated risks from natural or man-caused catastrophes. (See Figure 1-5). The 1993 carbon fiber risks appear to be several orders of magnitude lower (in terms of economic losses from a single event with fixed probability) than the risks from hurricanes, mining disasters, or even nuclear power plant accidents. These other events are also a threat to human life, whereas the risks to humans from carbon fibers are not yet well-established. Preliminary experiments have shown that there is a potential for CF creating a shock hazard in appliances such as toasters, but there are not sufficient data to support a risk assessment.

A qualitative analysis of the various stakeholders was performed to determine the relative impacts upon them of CF risks. These stakeholders include private citizens, CF producers, industries utilizing or manufacturing electronic equipment, and in particular the aerospace industry. Several alternative methods for reducing the risk are conceivable, although the desirability of a risk control policy would not be apparent without a careful examination of the costs and benefits to the stakeholders.

There are several areas which warrant further investigation, so that a more definitive assessment of CF risk may be obtained. These include a refinement of the CF utilization forecasts, further tests of the actual physics of CF release and dispersion, further tests of equipment vulnerability, and a more thorough analysis of economic impacts - particularly with respect to future developments at airports and in the rapidly-growing electronics industry. By providing the simulation model with more detailed probabilistic descriptions of some of the input parameters, a more accurate risk profile could be obtained with narrower uncertainty bounds.

FIGURE 1-5

COMPARISON OF RISK PROFILES



2. INTRODUCTION

2.1 OVERVIEW OF THE CARBON FIBER PROBLEM

There has been a noticeable trend in recent years towards utilization of carbon fiber composite structures as an alternative to metals in both civilian and military applications. Carbon fiber composites are valued for their light weight and high strength as well as for the ease of designing composite structures with specific shapes and properties. The major areas in which use of these materials is expected to grow include military and civilian aircraft, space systems, automobiles, sporting goods, and various industrial applications. Since unit production costs are expected to decrease, carbon fiber composites will become increasingly attractive as alternative materials, offering the benefits of reduced weight together with improved performance. However, a problem may exist due to the high conductivity of the carbon fibers.

Carbon fiber composites are manufactured from a precursor material which is subjected to great stress and heat treatment, causing a change in the physical and electrical properties of the fiber. The resulting fibers are then bound in a matrix of epoxy according to the required design specifications. The fibers are approximately eight micrometers in diameter, and a small cross-section of composite structure will contain millions of these fibers. Because the epoxy matrix is flammable, if the composite were involved in a fire the epoxy could burn away, and carbon fibers could conceivably be released and could disperse in the atmosphere. When these fibers come into contact with electronic equipment, they might cause damage by settling on electrical junctions. Fibers released in this manner would probably range from one to ten or more millimeters in length, would be extremely light, and could travel over large distances before lodging in a unit of equipment.

The first evidence of the type of damage that could result from release of carbon fibers occurred in Fostoria, Ohio in 1972 [1]. Carbon fibers 6 to 42 inches long were accidentally placed in the incinerator of a fiber production facility, were released from the smoke stack, and sub-

sequently settled on electrical substations at the plant, causing short circuits and an interruption in power. The possibility of damage has since been confirmed by laboratory tests in which electronic equipment was exposed to various quantities of carbon fibers. The mechanism of damage can be of three different types: resistive loading, temporary short circuits, or electrical arcing. These phenomena are generally associated with low voltage equipment, and microcircuitry may be particularly vulnerable due to the small spaces between contacts.

Given the existence of this damage phenomenon, there is reason for concern that future accidental releases of large quantities of carbon fibers might cause significant disruption or damage to electronic equipment over a fairly large area. In particular, commercial aircraft, which may soon carry a considerable mass of carbon fibers, are susceptible to infrequent accidental fires during their normal operating cycle. These fires are sometimes accompanied by explosive agitation and high impacts which may contribute to the release of fibers. As a result, there could be an effect not only upon electronic guidance and navigation equipment at the airports, but also upon industrial and residential equipment located in nearby communities, causing both direct and indirect economic losses.

Single carbon fibers are extremely light, and are comparable to large dust particles in buoyancy. Thus, a carbon fiber cloud created by fibers released from a burning aircraft could conceivably rise in a thermal plume and disperse over long distances, depending upon the weather conditions. The fibers themselves are sufficiently fine to penetrate cracks in buildings and possibly pass through filters, so that significant exposures might result in the interiors of buildings. Having entered the buildings, the fibers could penetrate equipment cabinets through cracks or vents and cause damage, unless the equipment is sealed or coated with a protective lacquer. Being extremely inert, the carbon fibers may remain a problem for some length of time, since they may deposit upon surfaces and be subsequently reentrained long after the initial incident.

Aside from the impact on electronic equipment, there is still some question about the possibility of shock hazard due to the grounding of

equipment cabinets which are subject to human contact. An additional area of concern is the possible effect of inhaling carbon fibers from ambient air. Although early evidence indicates that carbon fibers are not a health hazard, the health concern is still being studied by the National Institute of Occupational Safety and Health and the Environmental Protection Agency. However, the principal issue addressed in this study was the economic loss resulting from equipment damage. Potential shock hazards are discussed in Chapter 12.

The National Aeronautics and Space Administration (NASA) has been assigned the role of coordinating a program of investigation of the possible impacts of carbon fiber releases due to commercial aircraft accidents. Their objective is to amass a sufficient amount of data to permit quantification of the risks from carbon fiber releases, and to estimate the magnitude of these risks to the nation as a whole. Several other U.S. government agencies are addressing additional aspects of the problem, such as potential releases from automobile accidents, from manufacturing or industrial operations, or from commercial shipments of composite structures. These agencies include the Department of Commerce, the Department of State, the Department of Transportation, the Department of Health, Education and Welfare, as well as NIOSH and EPA.

A comprehensive investigation of the carbon fiber problem is necessary, so that the U.S. can weigh the costs and benefits of increased utilization of carbon fibers. If the potential costs resulting from damage to equipment are large in comparison to other risks, then it would be the responsibility of the above agencies to examine alternative courses of action that might effectively control the risk. However, any evaluation of risk must be performed in the context of the benefits which accrue to society from the use of these composites.

2.2 SURVEY OF EXISTING KNOWLEDGE

Recognition of the potential problems posed by the utilization of carbon fibers has led to a number of experimental investigations concerning the properties of these fibers. Earlier classified studies sponsored by the Department of Defense quantified the risk from aircraft accidents

at an individual airport. However, a need still existed for an in-depth analysis of the carbon fiber problem, incorporating all the knowledge available from multiple sources. Since the earlier risk assessment work, a great deal of experimental data has been produced, and a methodology was required by NASA for integrating these data into a comprehensive national risk assessment. Some of the pertinent areas of knowledge are listed next.

The phenomenon of release of carbon fibers from a burning composite structure has been investigated at the Dahlgren Labs, Naval Surface Weapons Center, Dahlgren, Virginia, through an ongoing series of tests using enclosed chambers. A variety of composite structures have been burned under various conditions including impacts and explosions during the burn. Depending upon the release conditions, from 5 to 25 percent of the fibers were found to be released as single fibers in an array of sizes. Other forms of fibrous materials, varying from lint to large clumps, in which the fibers had not yet separated completely, were also released. The fiber size spectrum ranged from single fibers, with lengths of approximately 1 to 10 millimeters, to lint - that is, groups of fibers adhering together - to large clumps in which the fibers had not yet separated completely. In a hypothetical accident scenario, the release of a carbon fiber mass would result in different dispersion behavior, depending upon the size of the particles released. For the purposes of this study we concentrated upon the release of single fibers, since these have the potential to travel farthest and are more likely to penetrate interior structures.

Tests have also been performed to determine fiber release information as well as to examine the phenomenon of fiber dispersion. An ongoing series of tests at China Lake in Nevada has attempted to measure the amounts of carbon fibers collected at various distances from the site of a large-scale fire involving an aircraft structure made of carbon fiber composites. Dispersion testing has also been conducted at Dugway in Utah. It appears that Gaussian plume models of fiber dispersion provide a good prediction of the actual dispersion of these fibers in the atmosphere. A particularly important variable in these models is the assumed settling velocity of the fibers. Depending upon the diameters of the single fibers, settling velocity can vary between 1 and 5 centimeters per second. The effect on the fiber cloud of a higher settling velocity is that the total mass of fibers settles to the ground more quickly, resulting in higher exposures closer to the release point.

Another ongoing series of tests to establish the penetration properties of fibers is being conducted by the Army Ballistics Research Laboratory, Aberdeen, Maryland, and Rome Air Development Center, Griffiss Air Force Base, New York. They have tested various types of commonly used filters to see what fraction of the fibers is permitted to pass through. Although these tests are intended to provide a basis for estimation of building penetration, the variability of conditions in the real world results in a wide range of possible filter efficiencies. Chapter 7 of this report will discuss this variability at greater length.

In the area of vulnerability of equipment to carbon fibers, a number of experiments are being performed by Bionetics, Ballistics Research Laboratory, and Rome Air Development Center. By subjecting units of equipment to successively higher levels of exposure, using fibers of various lengths, they have been able to induce failures in certain types of equipment. The exposure levels at which different units failed have been compiled, and these data were used as a basis for the vulnerability estimates described in Chapter 8.

Despite the knowledge gained from the above experimentation, there are still a number of unresolved areas having to do with the potential carbon fiber release from an actual aircraft fire. The air-frame manufacturers have been conducting an ongoing investigation for NASA in order to better predict what portions of an aircraft might be involved in an accidental fire, and the amounts of carbon fiber composites expected to be present in different portions of the aircraft in future years. Other ongoing tests are aimed at confirming the possibility of carbon fibers released from an actual burning composite structure being able to damage equipment at a remote location. Experiments are being conducted both in a shock tube at the Dahlgren Labs and in outdoor tests. These tests are expected to establish that fibers dispersed downwind from a burn can in fact cause equipment failure.

The types of investigation cited above are aimed at resolving the uncertainty surrounding the release, dispersion, and damaging impact of carbon fibers. Although the uncertainty can never be completely resolved, it may be possible to increase our knowledge to the point where the level of uncertainty is acceptable, and where the conclusions of a risk analysis based upon these experimental results can be defended with confidence.

2.3 OBJECTIVES AND STUDY OUTLINE

The overall objective of the present study was to estimate the risk to the U.S. as a whole, over the period from the present day until 1993, from accidental releases of carbon fibers in commercial air carrier accidents. This objective may be broken down into a number of subsidiary objectives.

- Project the growth of the market for carbon fiber composites in the U.S., and the utilization in commercial aircraft.
- Take into consideration the largest airports in the U.S., in terms of total operations, as potential sites of air carrier accidents or incidents.
- Analyze the possibilities of an accidental release of carbon fibers in a scenario involving either fire or fire followed by a delayed explosion.
- Estimate the resulting exposures in the area surrounding the accident location due to dispersion of fibers in the atmosphere.
- Identify equipment and facilities which are potentially vulnerable to damage from carbon fibers that penetrate to electrical junctions.
- Assess the potential economic losses, either equipment repair and replacement costs or business interruptions, resulting from the failure of electronic equipment.

In order to achieve the above objectives several steps were necessary. These included the gathering of data to support our analysis, the development of a methodology to analyze these data and to describe the physical mechanisms involved, and the development of a model to simulate the actual release incidents in order to permit an evaluation of national risk. The performance of these three steps is discussed below:

- Data Gathering - Through literature reviews and field surveys, data were gathered concerning the utilization of composites in commercial aircraft, the incidence of aircraft accidents in relation to total air carrier traffic, the known experimental

results concerning release, penetration and vulnerability as described in the previous section, the total population of facilities potentially exposed to carbon fiber releases, and the economic losses resulting from equipment failures.

- Methodology Development - In order to describe the physical mechanisms involved in the sequence of events leading from release of carbon fibers to economic impacts on society, we drew upon statistical techniques, engineering and physical models, and microeconomic models. The combination of these models into a comprehensive methodology for risk measurement is described in Section 2.5 below.
- Simulation Model - Once the underlying mechanisms of an individual accidental release and dispersion scenario were understood, it was necessary to develop a simulation technique which would permit repeated iterations of hypothetical accidents in order to develop an estimate of national risk. This was accomplished using Monte Carlo simulation methods as described in Chapter 11.

To satisfy the study objectives, the methods developed above were applied to available data in order to compute a mean and range for the national risk in the years 1985 and 1993. In order to effectively describe the range of national risk, we made use of risk profiles which relate various levels of economic losses to the probability of sustaining these losses. Risk profiles are discussed in Section 2.4. To increase the usefulness of these results, sensitivity analyses were performed to investigate the effect of changing certain variables upon the overall risk. By assuming different levels of carbon fiber utilization, building penetration, or other factors, we were able to examine the resulting change in the risk profile, and thus to determine which factors were most critical. Based upon the results of the risk evaluation, a stakeholder analysis was performed to identify the various parties affected by the risk and the implications for each. Finally, a comparison was done between the risks presented by carbon fiber releases from air

carrier accidents and other risks, whether voluntary or involuntary, to which we are exposed on a national level.

2.4 REVIEW OF RISK ANALYSIS PRINCIPLES

The concept of risk can be defined as follows[3] risk is the potential for realization of unwanted negative consequences of an event or activity. In the case of this study, the unwanted negative consequences are the potential economic losses due to electronic equipment failure. The event or activity in question is the operation of commercial aircraft utilizing carbon fiber composites.

In the past decade, an increasing amount of attention has been paid to problem areas involving activities with uncertain outcomes which might engender large risks. In order to deal with these problems the field of risk management has been created and developed. Risk management is a methodical scientific approach towards dealing with such risks. The quantitative aspects of risk management are often referred to as risk analysis. Examples of the application of this approach are in the areas of nuclear reactor safety and transportation of hazardous chemicals, such as liquefied natural gases.

The practice of risk management involves three basic steps: risk identification, risk measurement, and risk control. Potential risks can be identified through experience, judgment, or experimentation. In the case of the carbon fiber problem the nature of the risk is fairly well understood. The major challenge lies in risk measurement, that is, in determining the frequency of occurrence of events. Thus, the purpose of risk analysis is to create an analytic framework permitting assessment or measurement of risk. Finally, if the measured risk is considered sufficiently great, control measures may be deemed necessary. Control measures would consist of any modifications to the mechanism of risk resulting in a reduction in the measured risk.

There are various possible representations which can be used to quantify risk. One possible representation is the expected value of losses over a given period of time. However, in order to deal with risks

which may fluctuate over a wide range of losses and a correspondingly wide range of frequencies of occurrence, a preferred method of representation is the risk profile. A hypothetical example of a risk profile is shown in Figure 2-1. The activity in question is labeled Activity 1 and the risk profile for Activity 1 shows that economic impact can vary from \$100,000 to \$10 million with probabilities ranging from one in a thousand to one in ten thousand. This risk profile may be compared against other profiles for different types of events, such as the damage from tornadoes. In the diagram two comparator risk profiles are shown. If risk control options are exercised, it may be possible to reduce the risk from Activity 1 as shown by the dotted curve at the bottom. The vertical lines are confidence bounds which show the uncertainty in the estimates of risk. Even though the actual risk may fall anywhere between these confidence bounds, the risk profile can still be used as an effective decision-making tool since it both quantifies in an absolute sense the risks imposed by Activity 1 and permits a comparison of these risks relative to other known risks.

2.5 APPROACH AND METHODOLOGY

The overall approach that was adopted for estimating the national risk from carbon fibers was to create risk profiles for specific airports within the U.S., and to combine these risk profiles along with the potential risk from cruise accidents into an overall national risk profile.

The risk analysis methodology developed for determination of risk profiles at specific airports is summarized in Figure 2-2. The first step was to compute the probabilities of various accident scenarios taking into account the specific airport characteristics (such as weather conditions) and the aviation statistics on accidents and total operations. An accident scenario consists of specific details such as the type of aircraft, the location of the accident, and the level of damage sustained. After an accident scenario had been specified, the carbon fiber release conditions corresponding to the scenario were determined. The release conditions were dependent upon the severity of the fire and its duration, the weight of composites present in the aircraft, and whether an explosion

FIGURE 2-1

HYPOTHETICAL RISK PROFILE

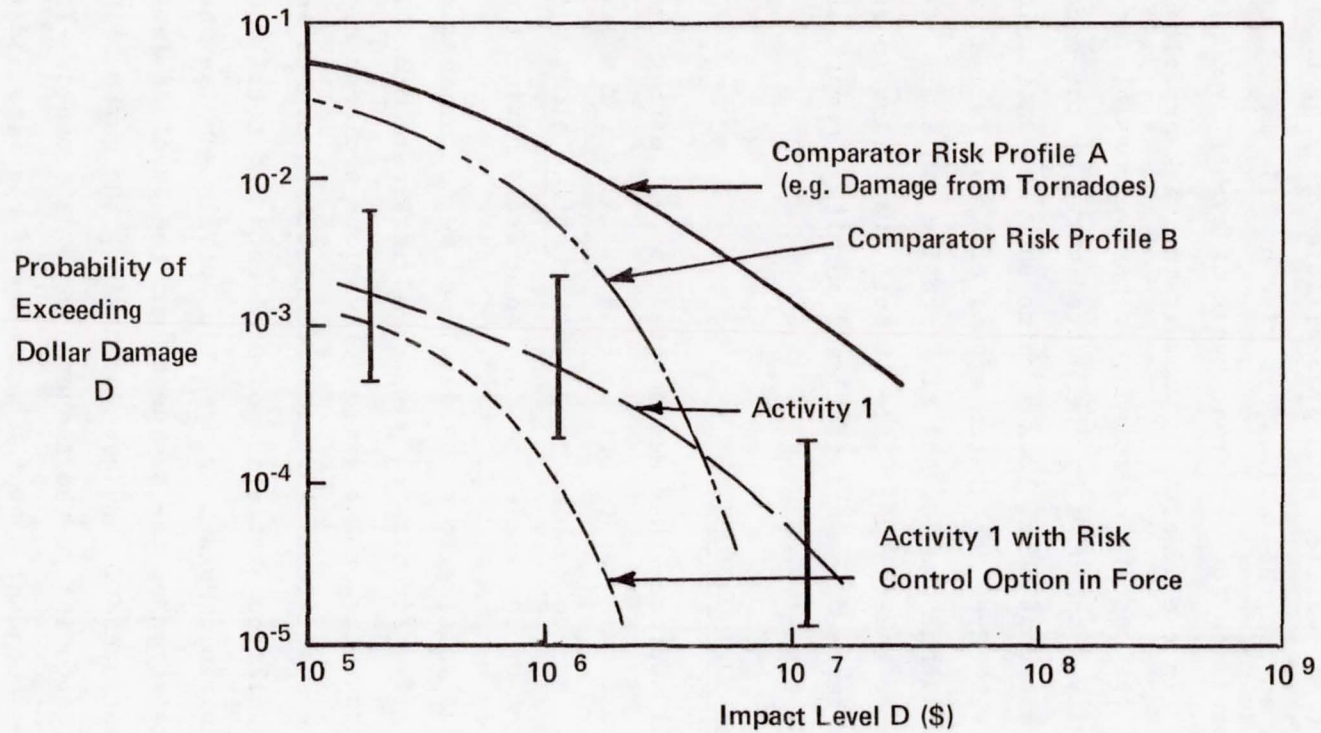
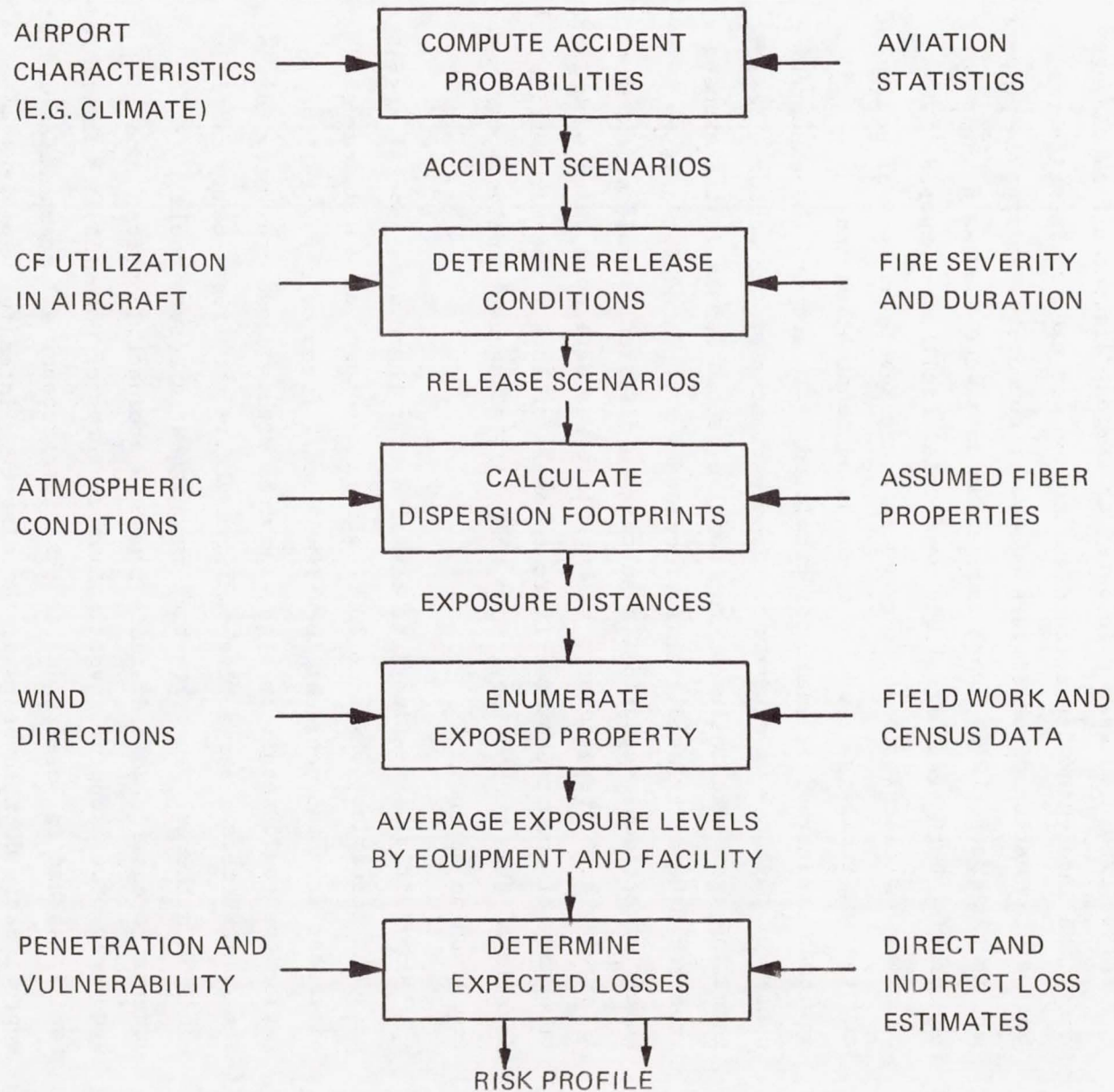


FIGURE 2-2

OVERVIEW OF RISK ANALYSIS METHODOLOGY



occurred. These release conditions were then fed as input to a dispersion calculation which incorporated certain assumptions about the settling velocity and other fiber properties. The resulting exposure levels were a function of the atmospheric conditions at the time of the accident.

After exposures were calculated at various distances from the accident, the local wind direction distribution was used to identify the path of the carbon fiber dispersion and to enumerate the exposed property within that path. Field work and census data were used as a basis for enumerating both residential and commercial facilities exposed. The outcome was a calculation of average exposure levels by type of equipment and type of facility. Results of building penetration and equipment vulnerability analyses permitted us to compute the expected number of failures of equipment. From estimates of the economic losses resulting from such failures, the total expected losses in the exposed area could be calculated. This procedure was repeated for a large number of accident scenarios, resulting in different levels of expected loss. After many such iterations, a risk profile was developed which showed the frequency of occurrence of different levels of loss. The mathematical details of this methodology, upon which all subsequent analysis was based, are given in Appendix A.

Our initial investigations revealed that there were several possible accident scenarios, which could result in exposures at a wide range of distances from the accident location. Small fires or fires followed by explosions could result in high exposures within close proximity to the accident, whereas a large fire could result in the fibers being carried aloft in a thermal plume, so that the highest exposure could occur at a considerable distance from the accident location. Consequently, the scope of investigation in terms of potentially vulnerable facilities had to be expanded to take into account all communities within approximately 80 kilometers of the airport. Intensive case studies in the vicinity of a few airports would not have been sufficient to reveal the total extent of possible damage. We settled on the approach of examining all the large hub airports in the United States by performing an

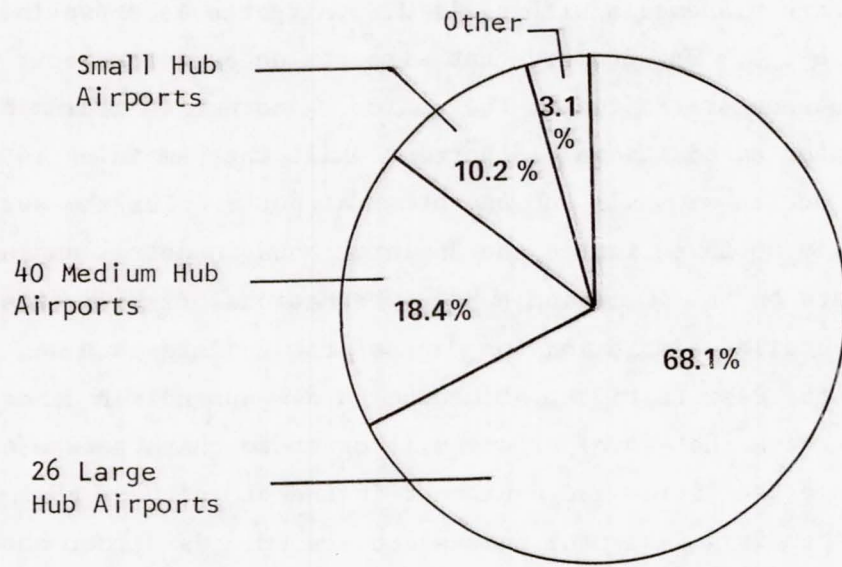
exhaustive enumeration of the facilities lying in various regions surrounding the airport. The 80 kilometer radius was sufficient to encompass most dispersion scenarios, although in a few cases our dispersion model predicted that this radius would be exceeded. By placing the airport at the center of a circular grid and identifying the precise accident location relative to the airport center, we were able to compute anticipated exposure levels over the entire area for any given release conditions.

The choice of airports to be examined in the risk analysis was dictated by the FAA Aviation Statistics [2]. The distribution of total passenger enplanements within all U.S. airports is shown in the chart of Figure 2-3. The 26 large hub airports account for about 68 percent of the passenger traffic in the nation. Another 40 medium hub airports account for an additional 18 percent while the remaining 14 percent of traffic occurs at small hub and other airports. For the purposes of this study we investigated the 26 large hubs in detail and also accumulated data on the 40 medium hubs. The national risk profile was based upon a detailed simulation for each of the 26 large hub and an extrapolation of the results to the 40 medium hubs. Appendix B describes the field surveys that were performed in order to characterize the potentially vulnerable facilities and equipment in the vicinity of these airports, while Appendix G lists the census and economic data that were gathered to support the economic loss analysis for each large hub city. A listing of the large hubs is provide in Table 2-1, showing total passenger enplanements according to FAA statistics. These 26 hubs account for 59% of air carrier operations in the U.S.

To carry out the approach described above, a team of professionals was organized, representing expertise in a number of different disciplines. Our team included experts in the fields of operations research and simulation, dispersion modeling, fire and safety technology, electronics, engineering, and economics. This report is organized along the lines of inquiry established by the case team. Chapter 3 describes the projected market for carbon fiber composites. Chapter 4 presents our accident probability analysis, while Chapter 5 describes the carbon fiber release

FIGURE 2-3

DOMESTIC AIR CARRIER OPERATIONS



Percent of Passenger Enplanements

Source: 1977 Airport Activity Statistics - FAA, CAB

TABLE 2-1

SCHEDULED AIRLINE TRAFFIC AT LARGE HUB AIRPORTS

FISCAL YEAR 1975

	Passengers Enplaned	Aircraft Departures
Atlanta	12,294,599	197,347
Boston	4,847,846	87,161
Chicago	15,904,449	276,723
Cleveland	2,699,465	57,283
Dallas-Fort Worth	7,068,238	136,737
Denver	5,383,894	98,179
Detroit	3,636,453	78,217
Honolulu	4,215,356	38,157
Houston	2,750,007	52,918
John F. Kennedy	6,627,695	97,394
Kansas City	2,107,467	51,867
Las Vegas	2,723,767	40,827
Los Angeles	8,782,950	134,119
Miami	4,683,269	76,671
Minneapolis	3,210,501	62,277
Newark	3,118,774	62,924
New Orleans	2,121,330	40,519
La Guardia	6,723,069	118,341
Philadelphia	3,333,943	69,404
Phoenix	1,964,856	42,956
Pittsburgh	3,498,323	87,132
St. Louis	3,511,987	85,512
San Francisco	5,971,444	107,233
Seattle-Tacoma	2,861,795	50,006
Tampa	2,290,901	45,851
Washington National	5,220,197	96,677

conditions. Chapter 6 analyzes the dispersion of carbon fibers in the atmosphere, and Chapters 7 and 8 deal with the building penetration and equipment vulnerability aspects of the problem, respectively. Chapter 9 presents the economic analysis of potential losses. Chapters 10 and 11 describe the simulation of a single incident loss profile and the synthesis of a national risk profile from the individual airport profiles. Finally, Chapter 12 presents a discussion and interpretation of the above results. A number of appendices are provided which list the data collected and the methodologies developed in the course of the above work.

The entire risk simulation effort was dependent upon the use of computer processing in several different modes. The simulation model used to calculate individual airport risk profiles was a combination of two in-house models, appropriately refined for the purposes of this study. One was a business venture model which performed the Monte Carlo iterations, and the second was a dispersion model used to calculate dosage at various geographic points. These two models were linked and modified for application to carbon fiber releases, and the combined system was tested on an IBM 370/138 in-house computer. The subsequent simulation runs were performed on an IBM 370/168 provided by an outside vendor; the outside service was used due to more rapid processing times. The combination of risk profiles to produce a national risk profile was performed on an IBM 5100 portable computer as well as on the in-house computer. This latter part of the analysis was performed in APL (A Programming Language) whereas the simulation model was written in FORTRAN. Development of these computer programming methods has resulted in a powerful tool which is applicable to future investigations of accidental releases and the resulting economic losses.

2.6 REFERENCES

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3. MARKETS FOR CARBON FIBER COMPOSITES

3.1 INTRODUCTION

A growing market exists in the United States for the use of carbon, or graphite, fibers in civil aircraft. This chapter describes the results of our investigation of this carbon fiber market. The forecasts developed here will be used as a basis for the carbon fiber release conditions in Chapter 5.

Our overall objectives in this task were to estimate the current (1977) carbon fiber (CF) market by sector, to forecast the CF market to 1993, to characterize the civil aircraft sector, and to identify competitive materials. To accomplish these objectives, we have conducted a literature search, held discussions with appropriate ADL staff members, carried out telephone interviews with manufacturers and users of carbon fibers, and held personal interviews with individuals familiar with carbon fiber technology and usages.

3.2 CARBON FIBER UTILIZATION

3.2.1 Carbon Fiber Technology

3.2.1.1 Precursor

There are basically three types of CF on the market today. The differences arise from the starting material or precursor used; viz., rayon, pitch, and polyacrylonitrile, which is commonly referred to as PAN. CF was initially produced with a rayon-based material; however, it was found that processing and property advantages could be gained by using polyacrylonitrile, as the rayon produces a more costly product, is more difficult to process, and has a lower carbon yield. More recently, Union Carbide has introduced a carbon fiber made from pitch. The expectation with pitch-based fibers is that they eventually will match the properties of PAN-based material, but will be more economically attractive due to the inherent lower cost of pitch as a precursor and its higher carbon yield. To date, however, the physical properties of the pitch-based fibers are less reproducible than PAN-based material.

3.2.1.2 Processing

The processing of each of the precursors into carbon fibers can be described by three processing steps:

- (1) a low-temperature preoxidation treatment;
- (2) a medium-temperature carbonization treatment; and
- (3) a high-temperature graphitization treatment.

The low-temperature preoxidation step is carried out in an oxidizing atmosphere in the 200-300°C range for several hours. During this stage, water and complex tars are driven off and a char suitable for carbonization is formed. This step is used to promote cross-linking, thereby stabilizing the precursor.

The next step is carbonization of the preoxidized fiber in which the fiber is heat-treated in an inert atmosphere at temperatures between 1000-1500°C. This step drives off essentially all of the remaining foreign materials, leaving behind a nongraphitized, therefore nonconducting carbon filament.

The third step is the graphitization of the fiber which is accomplished by heating the fiber to the 2500-3000°C temperature range for very short periods of time, again in an inert atmosphere, to prevent oxidation of the fiber.

In addition to the three heat-treating steps in the processing of a precursor into carbon fiber, a stretching operation is also carried out. The purpose of this operation is to promote a more ordered structure in the final fiber by alignment and growth of the hexagonal carbon rings. These rings align themselves such that the basal plane is parallel to the fiber axis. This stretching operation is carried out during the high temperature treatment for the rayon-based process and in the lower temperature regimes for the two other precursors.

The fibers are processed as tows which are essentially bundles of fibers containing 1000-160,000 filaments. These tows are then either wound into spools, woven into cloth, or chopped into mat.

3.2.1.3 Properties

The physical properties of CF differ markedly among each of the three types. Also, some differences exist in material produced from the same precursor, but from different suppliers. In general, and at the present time, the material produced from the PAN precursor yields a more desirable fiber in terms of elastic modulus and tensile strength, and in reproducibility. Typical properties for CF are:

<u>Physical Properties</u>	<u>PAN</u>	<u>Rayon</u>	<u>Pitch</u>
Tensile Strength, MN/m ² (psi)	2070-3100 (300-450x10 ³ *)	830-2480 (120-360x10 ³ *)	690-1380 (100-200x10 ³)
Tensile Modulus, GN/m ² (psi)	210-530 (30-77x10 ⁶ *)	410-480 (60-70x10 ⁶ *)	240-690 (35-100x10 ⁶)
Density, g/cm ³	1.8-1.9	1.5-1.8	1.8-2.0

The differences between manufacturers using the same precursor are due to processing or temperature differences. Higher processing temperatures tend to yield higher density and high elastic modulus fibers, whereas strength increases initially with processing temperatures, reaches a maximum and then begins to decrease.

As with strength and modulus, electrical resistivity varies among the different types of fibers. As would be expected, the more ordered or highly graphitized fibers have lower electrical resistivity. A typical resistivity value would be in the order of 10^{-3} ohm·cm for a PAN-based material.

3.2.2 Carbon Fiber Markets, 1977

There are presently 15 firms producing carbon fibers; of these Toray of Japan is the single largest producer. The U.S. market is serviced by 7 firms, of which Union Carbide, through their Toray suppliers, is the largest. Hercules is second with about one-half the sales volume of Union Carbide and together they comprise about three-quarters of the total U.S. market. Approximately 20% of the U.S. market is serviced by Stackpole Fibers, Celanese and Great Lakes Carbon.

* Power of ten goes with both extremes of the range; e.g., 300-450x10³ means the range 300x10³ to 450x10³. The conversion factor is psi(6.894757)(10)³=N/m².

The total market is estimated to be about 150,000 kg. and has been growing at a rate of about 47% per year since 1974.

The CF market may be subdivided into four sectors: sporting goods, aerospace, industrial, and a miscellaneous sector. The present market share of these various sectors is given in Table 3-1.

3.2.2.1 Sporting Goods

The sporting goods sector of the CF market is the single largest sector. It has about a 41% market share, consuming about 61,000 kg. of fiber per year. Applications include golf shafts, ski poles, skis and fishing poles. The sporting goods sector is continuing to expand due in part to lower manufacturing costs and, to a lesser extent, because of lower fiber cost.

3.2.2.2 Aerospace

The aerospace sector, which presently is dominated by military/ government applications, consumed about 50,000 kg of CF in 1977 or 33% of the market. Civil aircraft consumed only about 5,000 kg. of fiber. Applications include tails, ailerons, spoilers, elevators, slats, cowls and rotors. Currently each of the three major civilian aircraft manufacturers, Douglas Aircraft Company, Lockheed - California Company, and Boeing Commercial Airplane Company, are assessing the potential of CF composites in their respective aircraft under NASA funding.

3.2.2.3 Industrial

The industrial sector which includes automotive and marine applications presently consumes about 15,000 kg. or 10% of the total market. The automotive portion of the sector accounts for about 25%. Textile and other machinery parts, x-ray equipment, and sound system components also are included in this sector. Potentially the industrial sector (automotive) could become the major user of CF.

3.2.2.4 Other

The remaining applications for CF, primarily R&D usage, accounted for about 24,000 kg. or 16% in 1977.

TABLE 3-1

PRESENT (1977) CF MARKET BY SECTOR

<u>Sector</u>	<u>Market Share</u>	
	<u>(%)</u>	<u>(1000 Kg)</u>
Sporting Goods	41	61
Aerospace	33	50
Industrial	10	15
Other	16	24
Total	100	150

Source: ADL estimates

3.2.3 Forecast to 1993

During the next 15 years we expect the carbon fiber market to grow at an average annual rate between 25-30% per year. As mentioned above, the automotive industry has the potential to significantly influence the CF market and if its potential were realized, the usage of CF could, in 1993, be on the order of a billion kg. as opposed to our projection of nearly 6 million kg. If this realization were to occur, the cost of CF would be significantly reduced and in turn would have an impact upon other sectors (to varying degrees), hence upon our forecast. The aerospace industry is the least sensitive sector to CF costs and as such the magnitude of the automotive sector will have little if any effect upon the aerospace forecast and risk analysis.

During this forecast period we expect appreciable changes to occur between the various sectors as may be seen from Table 3-2. The growth rate of the sporting goods sector is expected to begin a decline in the near term (next five years) to about 20% per year and then level out to about a 5% per year growth rate. The aerospace sector is expected to change markedly; we expect the military sector to grow at about a 25-30% rate in the near term and about 10-15% in the long term. Of particular importance in the aerospace sector is the expected high growth of the civil aircraft sector. It is expected that the civil sector will grow at about 200% per year in the near term and at about 35-40% over the long term. As such the civil aircraft sector is expected to be about equal to the military sector by 1985, and be considerably larger (5 times) by 1993. The industry sector is expected to continue to grow at essentially the present level with little change between the near and long term, again assuming that the automotive sector does not mushroom rapidly.

3.3 CARBON FIBER UTILIZATION IN CIVIL AIRCRAFT

Civil aircraft is taken to include commercial aircraft, general aviation aircraft and commercial helicopters.

TABLE 3-2

FORECAST U.S. CARBON FIBER CONSUMPTION
(Thousands of Kilograms)

<u>Industry Sector</u>	<u>1980</u>	<u>1985</u>	<u>1993</u>
Sporting Goods	100	125	205
Aerospace:	90	160	400
Military and Government			
Commercial	35	180	1805
Industrial and Automotive	45	230	3320
R&D and Other	35	45	70
Total U.S.	305	750	5800

* Does not include production usage potential for approximately
15 x 10⁶ autos.

3.3.1 Commercial Aircraft

Since the USAF granted clearance to the Boeing Company on 13 July 1955 to modify their KC-135 transport into a commercial aircraft (B-707 and B-720) there have been approximately 5000 aircraft built and sold world-wide to commercial airlines by the three manufacturers (Table 3-3). This Boeing development (707, 720 and their subsequent aircraft B-727, which was introduced in 1962) has accounted for nearly one-half the total commercial aircraft manufactured to date in the United States. Over this period there have been essentially 400 aircraft built per year. Recently this figure has been nearly halved [1], but production is expected to increase markedly in the immediate future.

At the present time the use of CF in commercial aircraft is being investigated. Each of the "Big Three" aircraft manufacturers, Douglas, Lockheed and Boeing, is and has been conducting service tests of CF composites through the NASA funded ACEE program. In this program each of the three manufacturers is assessing the use of CF in at least two areas of one of their aircraft. The first use of CF in commercial aircraft was by Boeing (B-737) in an epoxy matrix spoiler application in July 1973, which after five years and 1,031,000 hours of flight service evaluation on 111 components showed only minor maintenance and operational problems. All but one have been repaired and returned to service. On a subsequent series of spoilers manufactured by Boeing with a polysulfone matrix, the polysulfone resin was attacked by hydraulic fluid after six months in flight service and all 12 polysulfone spoilers were withdrawn from the service evaluation [2], [10].

Commercial aircraft manufacturers have indicated that the most economical manner in which to incorporate CF is in initial design applications and not in retrofitting, the reason being the considerable costs associated with redesigning a component using a different material. Therefore, it is believed that the major inroads for CF will be in new aircraft.

Prior to 1985, it is not expected that CF components will be used in primary structure applications in commercial aircraft. CF composites will be limited to control surfaces, leading edges, various fuselage

TABLE 3-3

CUMMULATIVE PRODUCTION OF COMMERCIAL AIRCRAFT

	<u>Boeing</u>				<u>Lockheed</u>	<u>McDonnell-Douglas</u>		
Type of Craft	B-707	-727	-737	-747	L-1011	DC-8	-9	-10
Year First Delivered	1958	1962	1967	1969	1972	1959	1965	1972
Number Delivered	912	1448	517	303	139	556	887	238
*Mid-1977)								
Avg.Per Year to 1977	48	965	52	38	28	31	74	47.5

Total Aircraft Delivered = 5000

Annual Average for Period = 415

Source: Jane's All the World's Aircraft 1977-1978, 1973-1974

sheathing applications, and other secondary structures. NASA and the aircraft companies estimate that by 1985 CF will constitute about 180 kg. of an aircraft's weight on the average.

Between 1985 and 1993 more widespread use of CF is expected in jet aircraft such as in cowlings, fins and flooring, so that the average usage estimated by NASA and the aircraft companies is about 900 kg. per aircraft. Hence, by 1993 the commercial aircraft CF market could be at about the one million kilograms per year level.

Generally speaking, an aircraft has a serviceable life of about 20 years. Given this life, the majority of the present U.S. airline fleet, which numbers approximately 2600 aircraft,* would have to be replaced during the next 15 years (by 1993). Presently, the three U.S. aircraft manufacturers have been producing their jet aircraft in a ratio of 25% small aircraft, 60% medium and 15% large. It is expected and has been assumed that this ratio will be maintained through 1993.

Following is a comparison of the usage and projections of CF between our estimates and those as given to us by NASA as estimated in a recent meeting with the U.S. aircraft manufacturers [8].

Tables 3-4 and 3-5 show the ADL and the NASA fleet mix and carbon fiber usage projections, respectively, and are included for comparative purposes. The NASA projections were used in all of the subsequent risk analysis.

3.3.1.1 Large or Jumbo Class

In 1977 there were 316 jumbo jets in the U.S. airline fleet [1]. This number is expected to increase to about 475 in 1985 which would then imply an average production rate of 20 per year. Prior to 1982, essentially no CF will be used on these aircraft, however the average CF mass of those carrying fiber in 1985 is expected to be about 500 kg. per craft. The NASA estimates indicate that about one-third of the jumbo fleet will be carrying fiber at that time. This estimate appears somewhat high, since between 1982 and 1985 we estimate that only about 80 jumbo jets would be carrying fiber, and as such would comprise only about 17% of the jumbo fleet.

* The numbers cited for each class of aircraft are for U.S. certificated air carriers and add up to less than 2600.

Given that the life of an aircraft is roughly 20 years, replacements of the jumbo jets will begin in about 1990. By this time, we expect the jumbo fleet to contain about 510 aircraft (based upon a yearly growth rate of nearly 2% per year), of which about 20-25% will contain carbon fiber. Production between 1990 and 1993 will be such that a total of about 290 will be produced or about 73 per year. This number corresponds to those jets placed in service prior to 1974 which would have to be replaced, as well as those required for the annual 2% growth rate. It is expected that 73% of the jumbo fleet in 1993 will consist of aircraft carrying carbon fibers, or that about 400 aircraft will be carrying CF of the total 550 aircraft in the jumbo fleet. The NASA figure projects a 50% fleet usage.

3.3.1.2 Medium Size Aircraft

In 1977 there were approximately 1300 medium size jet aircraft in the U.S. airline fleet [1]. This number is expected to grow at between 1-2% per year so as to reach about 1900 by 1985 and to be about 2200 in 1993. Replacement of this size aircraft is presently occurring as the first of these aircraft were put into service 20 years ago. Thus, between 1300 and 1350 of this type of aircraft will be replaced in the next 15 years. In addition, approximately 900 more will be required during this period for fleet expansion. Between 1982 and 1985 it is expected that nearly 160 of these aircraft will be built per year, and in this period they will begin to contain carbon fibers. In 1985 it is expected that about 25% of the medium size aircraft will contain some carbon fibers. Furthermore, it is expected that the average of those carrying carbon fibers will be approximately 300 pounds per aircraft.

In 1993 it is projected that 80% of the medium size aircraft will contain carbon fibers. In essence, the only medium size aircraft not containing carbon fiber will be those manufactured between now and 1982. Based upon our analysis we expect the medium sized aircraft in 1993 to contain an average of 550 kg. of carbon fiber, as compared to the NASA average figure of 700 kg. of CF per aircraft.

TABLE 3-4

ADL ESTIMATE OF FLEET MIX AND AMOUNT OF CF USED

	<u>1985</u>				<u>1993</u>			
	<u>% of Total</u>	<u>Carrying Fiber %</u>	<u>Fiber No.</u>	<u>Wt. of CF/ Aircraft (kg)</u>	<u>% of Total</u>	<u>Carrying Fiber %</u>	<u>Fiber No.</u>	<u>Wt. of CF/ Aircraft (kg)</u>
Small	25	23	167	80	25	76	634	360
Medium	60	25	475	120	60	80	1779	550
Large	15	23	109	330	15	74	411	1600
			<u>751</u>				<u>2824</u>	

TABLE 3-5

FLEET MIX AND AMOUNT OF CARBON FIBER USED
(As per NASA/AC Companies' Projection)

54

	----- 1985 -----			----- 1993 -----		
	<u>% of</u> <u>Total</u>	<u>%</u> <u>Carrying Fiber</u>	<u>Wt. of CF per</u> <u>Aircraft (kg)</u>	<u>% of</u> <u>Total</u>	<u>%</u> <u>Carrying Fiber</u>	<u>Wt. of CF per</u> <u>Aircraft (kg)</u>
Small	25	20	100	25	50	500
Medium	60	20	150	60	60	700
Large	15	33	500	15	50	2000

3.3.1.3 Small Aircraft

The small aircraft segment of the U.S. airline fleet is somewhat more complicated to analyze than the medium and large segments, as it contains a wide variety of aircraft from the twin jet engine to both the twin and four piston engine types. For purposes of this section of the report, the small aircraft segment consists of twin jet engine and four engine turboprop. However, only jet aircraft were considered in the risk analysis.

Prior to 1973 there were 641 of these aircraft in service in the U.S. airline fleet. Again assuming a 20-year life, we expect all of these to be replaced by small jet aircraft by 1993. As some of these aircraft were pre-1958, replacement is occurring presently. Given this replacement figure, over the next 15 years an average of 43 small aircraft per year will have to be manufactured just for replacement. In addition this segment is expected to grow at the 1-2% level over this period, hence it is expected that there will be about 725 of these aircraft in service in 1985 and approximately 830 by 1993.

Before 1982 essentially no usage of carbon fibers is expected on this type of aircraft. However, by 1985 it is expected that CF will be used on jets, and the average of those aircraft carrying fibers will be about 90 kg. per aircraft. Given the projected growth rate and the average annual aircraft replacement figure, it is calculated that approximately 23% of this type of aircraft will contain carbon fibers in 1985.

In 1993 this type of aircraft is expected to number about 830 or still about 25% of the total fleet. Of these about 75% will contain carbon fibers. Also, we expect that those aircraft manufactured in 1993 of this size classification will contain approximately 360 kgs. of carbon fibers. NASA estimates an average CF mass of 500 kg. per aircraft.

It should be noted that the present usage figure in our analysis is based upon the usage of carbon fibers by all airlines, and that no one airline will restrict its usage. This provides for a more conservative risk analysis.

3.3.2 General Aviation

In the past fifteen years the general aircraft industry sector has been growing at an average annual rate of approximately 6% per year (Table 3-6). Over the next fifteen years this growth rate is expected to continue. As such, production volumes will be about 40,000 aircraft in 1993 as compared to present volumes of nearly 17,000. In the near term however a somewhat higher growth rate is likely, as this sector has been growing at a 12% per year rate over the last five years, so that production should reach the 30,000 level by 1986.

Presently the market is dominated by three companies, Cessna, Piper and Beech who together comprise more than three-quarters of the total production volume, with Cessna being the single largest manufacturer. None of these three companies may be considered a proponent or leader of carbon fiber usage in this type of craft, although Cessna is contemplating some usage. The first production usage of CF is expected to come from Lear Aviation who has proposed its usage on their twin turbine executive class aircraft, Learfan. Original estimates for CF on this craft were about 300 kg. (500 kg. of composites), however, lower revisions to this estimate have been made. If indeed Lear does incorporate CF and finds that it has cost-performance advantages over present materials and other composites, i.e., fiber glass, Kevlar, then other manufacturers would follow. The belief at the present time is that CF is not cost effective for general aviation aircraft and therefore in the near term is not expected to be used. However in the meantime most manufacturers will purchase CF for evaluation.

By 1985 usage of CF in general aviation aircraft is expected to be less than 5 kg. per aircraft. However by 1993 usage could be sizeable if this material is proven to be cost effective. For example, if each craft contained 10 kg. of CF, a market of essentially 500,000 kg. would be realized.

3.3.3 Helicopters

Since 1970 U.S. commercial helicopter manufacturers have essentially doubled their yearly shipments from 482 to approximately 950 in 1977

TABLE 3-6

GENERAL AVIATION AIRCRAFT SHIPMENTS

By Selected Manufacturers
Calendar Years 1962 to Date

Year	TOTAL	Beech	Cessna	Gates Learjet	Grumman American	Piper	Rockwell Intl.	Other
Number of Aircraft Shipped								
1962	6,697	830	3,124	—	—	2,139	121	483
1963	7,569	1,061	3,456	—	—	2,321	114	617
1964	9,336	1,103	4,188	3	—	3,196	109	737
1965	11,852	1,192	5,629	80	—	3,776	110	1,065
1966	15,747	1,535	7,888	51	70	4,437	265	1,501
1967	13,577	1,260	6,233	34	52	4,490	386	1,122
1968	13,698	1,347	6,578	41	N.A.	4,228	471	1,033
1969	12,457	1,061	5,887	61	306	3,951	344	847
1970	7,283	793	3,730	35	217	1,675	211	622
1971	7,466	519	3,859	23	435	2,055	202	373
1972	9,774	802	4,964	39	620	2,461	242	646
1973	13,645	1,110	7,262	66	663	3,233	418	893
1974	14,165	1,303	7,187	66	628	3,415	545	1,021
1975	14,057	1,212	7,564	79	758	3,070	433	941
1976	15,447	1,220	7,888	84	762	4,042	595	856
1977	16,920	1,203	8,839	105	866	4,499	432	976

Growth Rate 1962-1977 = 6.4%

Source: Aerospace Fact and Figures
1977/78, 1975/76

(Table 3-7). At this growth rate, helicopter production for this sector should reach the 2000 level by 1985, and in all probability will double again by 1993.

At the present time two companies, Bell and Hughes, are the dominant manufacturers of commercial helicopters in the United States. Together they comprise more than 80% of this market. Relative to CF usage (in commercial craft) however, both are postponing any commitment. The principal proponent of CF usage in commercial helicopters appears to be Sikorsky in their S-76 craft. Proposed applications include stabilizers, rotors, and a doorframe stiffener. Hence, the status of CF usage in commercial helicopters is similar to that in the general aviation aircraft industry, namely that one aircraft manufacturer is proposing to include this material in an aircraft having a relatively high degree of composite, while the other manufacturers are taking a "wait-and-see" attitude. It appears that in the near term no significant usage of CF will occur in commercial helicopters. In the period beyond 1985 (to 1993) it is conceivable that CF will be used, and our order of magnitude estimate of use is in the range of 50 kg. per aircraft. As such the CF consumption would be approximately 250,000 kg. in 1993 for commercial helicopter usage.

3.4 COMPETITIVE MATERIALS

The materials presently available in fiber form which may be considered competitive to CF are fiber glass, Kevlar, oxide fibers and boron. Fiber glass does compete with CF, but it is deficient from a standpoint of its lower elastic modulus and its higher density. Kevlar can compete with CF, but it also has a lower modulus than CF. Furthermore, composites made from Kevlar have much poorer compressive strengths than CF composites. Also, oxide fibers, because of either their stiffness or density, do not compete with graphite in many of the applications currently being considered for or being fulfilled by CF. Boron fibers more nearly match the physical properties of CF than these other fibers except that they are much heavier than CF. However, because of their associated cost and handling difficulties, boron fibers are not considered

TABLE 3-7

U.S. HELICOPTER COMMERCIAL PRODUCTION

Calendar Years 1970 to Date

Company and Model	1970	1971	1972	1973	1974	1975	1976 ^r	1977
Number of Helicopters Shipped..	482	469	575	770	828	864	775	884
VALUE (Millions of Dollars)....	\$ 49	\$ 69	\$ 90	\$121	\$189	\$274	\$305	\$316
<u>Bell, Total.....</u>	<u>288</u>	<u>274</u>	<u>329</u>	<u>477</u>	<u>467</u>	<u>495</u>	<u>424^a</u>	<u>374^b</u>
47 Series.....	124	110	97	92	3	3	11	*
204 Series.....	-	1	-	4	-	1	2	*
205 Series.....	23	13	17	29	26	40	36	28
206 Series.....	138	129	193	304	368	325	290	283
212 Series.....	3	21	22	48	70	126	71	47
214 Series.....	-	-	-	-	-	-	13	9
AH-1J.....	-	-	-	-	-	-	1	7
<u>Boeing-Vertol, Total.....</u>	<u>-</u>	<u>5</u>	<u>6</u>	<u>2</u>	<u>11</u>	<u>10</u>	<u>11</u>	<u>12</u>
CH-47C.....	-	5	6	2	11	10	11	12
<u>Brantly-Hynes, Total.....</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>2</u>	<u>1</u>
B-2B.....	-	-	-	-	-	-	2	1
<u>Enstrom, Total.....</u>	<u>-</u>	<u>17</u>	<u>38</u>	<u>64</u>	<u>87</u>	<u>77</u>	<u>87</u>	<u>96</u>
F-28A.....	-	17	38	64	86	59	4	1
F-28C.....	-	-	-	-	-	-	40	43
280.....	-	-	-	-	1	18	3	-
280C.....	-	-	-	-	-	-	40	52
<u>Fairchild, Total.....</u>	<u>37</u>	<u>21</u>	<u>28</u>	<u>10</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>-</u>
FH-1100.....	37	21	28	10	-	-	-	-
<u>Hiller, Total.....</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>3</u>	<u>35</u>	<u>34</u>	<u>40</u>
12-E.....	-	-	-	-	3	35	29	35
12-E4.....	-	-	-	-	-	-	2	-
12-E (Turbine).....	-	-	-	-	-	-	3	5
<u>Hughes, Total.....</u>	<u>149</u>	<u>137</u>	<u>156</u>	<u>211</u>	<u>248</u>	<u>214</u>	<u>204</u>	<u>336</u>
300's.....	74	54	71	96	105	92	94	125
500's.....	75	83	84	115	143	122	110	211
<u>Sikorsky (UTC), Total.....</u>	<u>8</u>	<u>15</u>	<u>19</u>	<u>6</u>	<u>12</u>	<u>33</u>	<u>13</u>	<u>25</u>
S-61.....	6	9	13	6	12	13	13	25
S-64.....	-	-	-	-	-	3	-	-
S-65.....	-	-	-	-	-	17	-	-

Source: Aerospace Industries Association, company reports

NOTE: All figures exclude the production by foreign licensees

a Includes 6-206B and 1-AH-1J exported in a military configuration

b Includes 17-205 (UH-1H) and 7-AH-1J exported in a military configuration

r Revised

as a threat to CF. Conversely, CF fibers have been replacing boron fibers in many applications.

Presently there is not a material which is at such a stage of development that it poses a serious likelihood to replace CF in the near future. A potential candidate material might be boron nitride which could conceivably have similar properties to CF, with the exception that it is nonconducting and has the potential to be made by low-cost glass fiber-making processing techniques, coupled to a nitriding treatment.

3.5 REFERENCES

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4. PROBABILISTIC ANALYSIS OF AIR CARRIER ACCIDENTS

4.1 INTRODUCTION

In order to estimate the potential risks due to carbon fibers released from aircraft accidents, it was necessary to quantify the probability of an accident or incident at a major hub airport. This probability was contingent upon various conditions surrounding the incident including the phase of operation, aircraft type and the weather conditions. Furthermore, the type of accident predicted was categorized according to its location relative to the runway and the severity of damage sustained. The total set of conditions describing a given accident may be thought of as an "accident scenario". This accident scenario, in turn, determined a release scenario, which described the manner in which carbon fibers were released and the mass of fibers involved. Once a release had occurred, the dispersion analysis determined how the fibers were distributed relative to the accident site.

This chapter outlines the methodology utilized to estimate the probability of a specific type of accident, and describes the various models that were developed in the course of this work. The major source of data for the accident probability work was the NTSB accident reports, which are available either in the form of detailed reports, or in summary form on computer tapes. We used the tapes to examine overall statistics for air carrier accidents, and then scrutinized the detailed reports for a subset of about forty typical accidents involving damage due to fire and/or explosions. The resulting probability estimates were based on national statistics, but were then adjusted to reflect the particular weather conditions present at each major airport. The assumption was made that each air carrier operation at a given airport has a fixed probability of resulting in an accident, independent of other operations occurring at the same time or place.

4.2 DATA BASE OF ACCIDENTS

The data base utilized for the accident probability model consisted of the accident records compiled by the National Transportation Safety Board for the years 1968 through 1976. We considered all substantial damage and total destruction accidents or incidents for which there was a fire or explosion. NTSB identifies a fire or explosion accident in one of two ways. First, there are certain accidents caused by a fire or explosion, and second, there are accidents for which there was fire after impact. In almost every case, however, if a significant fire resulted, it occurred when the plane was on or near the ground. Hence, the two types of fire and explosion accidents categorized by NTSB are aggregated in our model.

The data base includes accidents or incidents involving U.S. air carriers throughout the world, as well as foreign carriers in the U.S. However, we accumulated operations data for U.S. airports only and considered only those accidents occurring in the U.S. The data that we extracted from each record included the following:

- Date
- Time
- Location (Airport)
- Takeoff, Landing, Overshoot, Taxi or Unattended Aircraft
- Aircraft Type (Make and Model)
- Weather Conditions (IFR, VFR, etc)
- Distance from Center of Runway
- Lateral Distance from Runway
- Level of Damage
- Cause of Accident
- Altitude (If Applicable)
- Fire after Impact
- Fire Damage
- Location of Fire
- Terrain
- Wind Direction
- Wind Velocity

The term operations refers to airport operations. That is, each landing and each takeoff is an operation. Although static and cruise accidents do not directly correspond to airport operations, their respective probabilities can still be computed in the same manner. Thus, the probability of an accident per operation can be interpreted as that number, which when multiplied by the number of airport operations at all airports, gives the expected number of total accidents.

To better describe the accident data base and the various subsets of the data base used to develop the model, Table 4-1 presents a summary of its contents. [13] This table also depicts the hierarchical relationships between the various accident frequencies referred to in this chapter.

The total number of substantial damage and total destruction accidents during the 1968-1976 period was 261. Of these, 81 accidents which involved a fire or explosion formed the basis for a great deal of our model-building work. These 81 accidents represent all aircraft types over a nine year period, and although they represent nine total fire and explosion accidents per year, this includes a smaller number of jet fire and explosion accidents per year. From the data for all total destruction and substantial damage accidents, only 131 out of 261 accidents were U.S. jet accidents. Thus, the expected number of jet accidents per year is:

$$\frac{131}{261} \times 81 = 4.5 \text{ per year}$$

9 years

For certain aspects of the model, there were not enough data in the fire and explosion data base of 81 accidents, and hence results were extrapolated from the full data base. (An example of this was the derivation of distance distributions for substantial damage of fire or explosion accidents. There were only 15 such accidents and we did not judge them sufficient to generate a distance distribution. Therefore, we extrapolated from 187 substantial damage accidents drawn from the entire data base.) Tabulations of the accidents in the data base appear in Appendix C.

TABLE 4-1

DATA BASE BREAKDOWN

A. *Accidents: National Data for All Aircraft*

Total number of substantial damage (SD) and total destruction (TD) accidents during 1968-76

261	
187(SD)	74(TD)

↓

Those including a fire or explosion

81	
15(SD)	66(TD)

↓

Those nonstatic accidents including fire or explosion

70	
34(IFR)	36(VFR)

}

B. *Weather: National Data*

Probability of IFR or below minimum weather during operations

$$P(\text{IFR}) = .1075$$

Probability of VFR weather during operations

$$P(\text{VFR}) = .8925$$

}

Probability of precipitation in IFR weather at the time of an accident

$$P(\text{PRECIP} | \text{IFR}) = .63$$

Probability of precipitation in VFR weather at the time of an accident

$$P(\text{PRECIP} | \text{VFR}) = .17$$

}

C. Accident Frequency by Aircraft Types: National Data

Total number of SD and TD accidents, 1968-76

261

Total SD and TD accidents involving U.S. aircraft

225

Total SD and TD accidents involving U.S. jet aircraft

131

Type of jet aircraft

Total SD and TD accidents per type

Total operations per type

Accident rate per type

Large

14

2.2×10^6

6.36×10^{-6}

Medium

80

35.4×10^6

2.26×10^{-6}

Small

37

27.7×10^6

1.34×10^{-6}

Average accident rate of all jet aircraft

2.01×10^{-6}

D. Fire or Explosion SD and TD Accidents by Operation Type: National Data

Total number SD and TD fire/explosion accidents

81

Type of operation

Total SD and TD fire/explosion by type

Takeoff

20

13(TD)

7(SD)

Landing

37

31(TD)

6(SD)

Cruise

13

9(TD)

4(SD)

Static/Taxi

11

3(TD)

8(SD)

In the course of completing our work we examined additional accidents during the period 1964 through 1967 and we noticed that there were differences from the 1968-1976 statistics. The biggest differences were that a) very few total destruction accidents in 1964-1967 took place on the airport, b) there was a higher percentage of cruise accidents during this period, and c) there were fewer landing accidents in this period. The first of these differences would have a significant impact on our accident probability model and the resulting risk profiles. While we cannot give specific reasons for these differences, it was noted that after 1968 there were changes in safety features, aircraft mix, and reporting procedures. Hence, the more recent data set is probably a better representation of future accident patterns. Furthermore, the data of Hewes and also of Nash [1,2] for British air carriers indicated that a high proportion of aircraft accidents take place on or near the runway. This, of course, is much more consistent with the period starting in 1968, and offers an additional support for ignoring the earlier data.

4.3 SELECTION OF IMPORTANT VARIABLES

The objective of the accident probability model was to derive an expression or a related series of expressions for the probability of an accident as a function of several variables. In methodological terms we were seeking a function of the form

$$P_T(V, A, W)$$

which represents the probability of an accident of type T (e.g., total destruction) at location V for operational category A (e.g., landing, jumbo jet) and safety factor (e.g., IFR weather) W. The definitions of these explanatory variables and the manner in which they are utilized are presented below.

In examining a variable to determine its impact on the accident probability model, two criteria were applied: First, are accident probabilities influenced by the variable? Second, does the variable affect carbon fiber dispersion? An affirmative answer to these questions resulted in inclusion of the variable in the accident scenario. An example of the importance of these issues was aircraft classification. After a careful analysis of the data, it was determined that for the purposes of the model, accident probabilities were independent of aircraft size. Aircraft type, therefore, was not a direct factor in the accident probability model. However, aircraft type has a significant effect on carbon fiber dispersion through the amount of carbon fibers released. For any given airport, therefore, the mix of aircraft types was utilized in determining the range of release scenarios. Even though aircraft class and size were important aspects of the overall analysis, we did not have to explicitly consider them in the accident probability model.

The first variable considered was the variable T, which describes the nature and severity of damage to the aircraft. We employed the standard NTSB classifications for damage, namely: total destruction, substantial damage, minor damage. The latter case was ignored, since it is unlikely that any carbon fibers could be released from a minor damage accident. We assumed throughout that fibers could only be released through a fire, and hence restricted our attention to accidents involving either a fire in flight or a fire after impact. An important detail in specifying the variable T was whether an explosion had occurred during the fire. If a burn were followed by a delayed explosion, this would very likely cause a large number of fibers to be released by mechanical agitation, once the composite structure had been burned away. The resulting dispersion would then be better described by an instantaneous release model, rather than the continuous-release fire plume model. (See Chapter 6)

Consequently, the four types of accidents considered were:

- Substantial Damage Plume Release Accident
- Total Destruction Plume Release Accident
- Substantial Damage Explosive Release Accident
- Total Destruction Explosive Release Accident

There are also minor accidents involving fire and explosion but, as explained above, we assumed that these would not cause a carbon fiber release. We also assumed that galley fires would not cause a release, since the duration and intensity of the burn would probably not be sufficient to destroy composite material.

Variable W, airport safety, incorporated two distinct parts. The first part reflected the probabilistic weather component which is reported at the following values:

- VFR for visual flight rules
- IFR for instrument flight rules
- Below minimum

It appears that this is a sufficient statistic for weather variables as they affect accident probabilities. (Of course, fiber dispersion depends on other weather factors such as wind speed and direction, but these do not appear to affect accident probabilities.)

The second part of the variable is the airport safety variable. This variable reflects the deterministic aspects of airport safety including terrain and physical facilities of the airport in a composite evaluation. After an extensive analysis of accident records and safety features for most of the major U.S. airports, we concluded that this latter part of the safety factor did not have a significant effect on accident probabilities. The details of this analysis are provided in Section 4.4.

Variable A was analyzed in two parts. The first part was the aircraft type and the second part was the operational category. The aircraft type defined the possible range of values for carbon fiber utilization. We considered 5 classes of aircraft: Jumbo jets, conventional

jets, small jets, turbo-props, and aircraft under 12,500 pounds. For the purposes of this study, we assumed that only jets will be utilizing carbon fibers by 1993; therefore these jets were divided into three aircraft categories. Presently, the aircraft in use within each category include the following:

- Jumbo Jet - Boeing 747, McDonnell-Douglas DC-10, Lockheed L1011, European Airbus A300B
- Conventional Jet - Boeing 707/720/727 McDonnell-Douglas DC-8. All Series, Convair 880/990, British Aircraft VC-10
- Small Jet - Boeing 737, McDonnell-Douglas DC-9, British Aircraft BAC 1-11; Dessault Mercure Aerospatiale Caravelle

We determined that aircraft types do not have a significant effect on accident probabilities (except, of course, for general aviation, which was not considered in this study). Therefore, we did not incorporate this variable within the accident model. We utilized aircraft type only to determine amounts of carbon fibers released in the accident simulation.

The operational phase was a significant part of the model since it had a noticeable effect on release conditions (take-off accidents, for example, would tend to have more intense fires since there is usually more fuel during take-off), and, in addition, the location distribution and frequency of accidents were found to be different for different operational phases. The phases incorporated into the model were the following:

- Take-off
- Landing
- Cruise
- Static or Taxi

The final variable was the location of an accident relative to the airport. This consisted of two components: the distance and angle from the runway. For the distance from the runway, we employed standard classifications from NTSB reports:

- On Airport
- In Traffic Pattern
- Within 1/4 Mile
- Within 1/2 Mile
- Within 3/4 Mile
- Within 1 Mile
- Within 2 Miles
- Within 3 Miles
- Within 4 Miles
- Within 5 Miles
- Unknown/Not Reported

In the NTSB reports, "distance" is defined to be the distance from the edge of the nearest runway. Take-off accidents were assumed to occur closest to the take-off end of the runway. Landing accident undershoots were assumed to occur closest to the landing edge of the runway, while overshoots were assumed to occur closest to the far edge. We analyzed distance distributions for the four operational phases and examined locations for accidents taking place on airports. For each of the large hub airports we also determined the frequency of usage of each runway.

The angle of incidence can be determined from lateral distance from the runway, which is sometimes entered directly on the NTSB reports. However, out of all the total destruction and substantial damage accidents in our data base (including those not involving a fire or explosion) there were only 40 off-airport accidents for which an angle of incidence could be determined and most of these were general aviation accidents. As a result, we utilized some outside data sources to estimate an angle of incidence distribution. All of the above analysis will be described in Sections 4.4 and 4.5 below.

4.4 STATISTICAL ANALYSIS OF ACCIDENT VARIABLES

In this section we present the analysis of all the variables in the model with the exception of accident location. (This is discussed separately in Section 4.5). These variables include safety, weather, aircraft class, type of accident, and operational phase.

The first variable that was examined was weather. Adverse weather may increase the probability of aircraft accidents, but in general, the IFR-VFR weather classification scheme gives sufficient information for accident purposes. In other words, the probability of an accident in IFR weather is generally independent of other weather factors (with an analogous result for VFR weather). Out of 70 accidents in our fire and explosion data base, 34 were either IFR or below minimum. (We excluded 11 static accidents caused by fire or explosion as we assumed that these were not affected by weather). There were also a few fire accidents for which the weather was unknown. We then examined the IFR-VFR weather mix of the major airports in the United States and computed a national probability of either IFR or below minimum weather. The value obtained was 10.75%. In computing this probability, weather mixtures at each airport were weighted by the number of operations at those airports.

The statistics indicate that the probability of an accident is significantly higher in IFR or below minimum weather. To develop a methodology to incorporate the impact of weather on accident rates, and to compute accident rates for each city, we utilized the following definitions:

$P(\text{IFR} \text{ACC})$	= probability IFR or below weather given an accident* occurred--national basis
$P(\text{VFR} \text{ACC})$	= probability VFR weather given an accident occurred--national basis
$P(\text{IFR})$	= probability IFR weather during operation--national basis
$P(\text{VFR})$	= probability VFR weather during operation--national basis
$P(\text{IFR}_i)$	= probability IFR weather at airport i during operation
$P(\text{VFR}_i)$	= probability VFR weather at airport i during operation

$P(ACC_i)$ = probability of an operation at airport i resulting in an accident (accident rate at airport i)
 $P(ACC)$ = probability of an operation in the nation resulting in an accident (national accident rate)

By the use of Bayes' theorem and the above definitions, expressions for accident rates for any given city can then be derived:

From Data Base Table 4-1

$P(IFR|ACC) = 34/70 = .4857$
 $P(VFR|ACC) = 36/70 = .5143$
 $P(IFR) = .1075$
 $P(VFR) = .8925$

From Bayes' Theorem

$$\begin{aligned}
 P(ACC|IFR) &= P(IFR|ACC) P(ACC)/P(IFR) \\
 &= .4857P(ACC)/.1075 = 4.5183P(ACC) \\
 &\doteq 4.52P(ACC)
 \end{aligned}$$

$$\begin{aligned}
 P(ACC/VFR) &= P(VFR|ACC) P(ACC)/P(VFR) \\
 &= .5143P(ACC)/.8925 = .5762P(ACC) \\
 &\doteq .58P(ACC).
 \end{aligned}$$

Thus,

$$\begin{aligned}
 P(ACC_i) &= P(ACC|IFR) P(IFR_i) + P(ACC|VFR) P(VFR_i) \\
 &= 4.52P(ACC)P(IFR_i) + .58P(ACC)P(VFR_i) \\
 &= [4.52P(IFR_i) + .58P(VFR_i)] P(ACC). \quad (4-1)
 \end{aligned}$$

The equation states that the probability of an accident in IFR weather or below is 4.52 times the overall accident rate and that the probability of an accident in VFR weather is .58 times the overall accident rate. Note that if a city had IFR and VFR weather probabilities equal to the national average, then $P(ACC_i) = P(ACC)$.

*Accidents assumed to be SD or TD with fire or explosion, and nonstatic

The major impact of weather in the overall carbon fiber risk analysis was in the dispersion model (Chapter 6). Dispersion greatly depends on the wind speed, wind direction, stability class, and temperature. Because of the lack of statistics on the correlation between IFR-VFR conditions and the above weather variables we assumed that these variables were independent of the IFR-VFR split. Hence, the impact of the IFR-VFR analysis above was in the computation of accident frequencies for each of the cities analyzed. For each city we computed the factor:

$$4.52 P(\text{IFR}_i) + .58 P(\text{VFR}_i) \quad (4-2)$$

This composite multiplier factor is multiplied by the national accident rate to compute an accident rate for each city as indicated in the above equation (4-1). Hence, if a city has a high percentage of IFR weather, the accident rate was assumed to be larger. The computed multipliers ranged from 1.19 for Los Angeles (15% IFR or below minimum) to .66 for Miami (1.9% IFR or below minimum). Although the theoretical computation was based on (4-1), the factor actually utilized was (4-2), from which we determined the relative importance of each city.

Other aspects of airport safety such as terrain, sophistication of instruments, etc. were incorporated into an airport safety variable ranging between 1 and 3. After examining accident rates in the past nine years for several airports and dividing these factors by the weather multipliers that we computed, we compared the overall accident rate for airports in each of the three safety categories. We concluded from a visual inspection that there was no basis for using different accident rates for airports in the three different categories. (In fact, the class of "safest" airports actually had a slightly higher accident rate.) We also computed some correlation coefficients between accident rates and each of several possible explanatory variables. From accident rates for 66 cities, (26 cities in the case of foreign operations) we obtained the following correlation coefficients (the R^2 values are the squares of the correlation coefficients):

rate versus index of facilities:	.21
rate versus safety variables:	-.18
rate versus percentage of foreign operations:	.74

Of these, only foreign operations percentage appeared to be significant.

The dependence on foreign operations appears to have been greatly influenced by the large numbers of accidents at Kennedy and Miami, the two airports with the highest incidence of foreign operations. We did not utilize foreign operations in determining accident rates at individual airports since the study was directed towards U.S. carriers, but in Chapter 11 we did adjust the mean number of accidents per year to account for possible foreign carrier accidents.

As an extension of the weather analysis, we examined the probability of precipitation at each of the airports, since rain or fog could have an effect on the carbon fiber dispersion. We determined that the probability of precipitation given an accident is larger than the unconditional probability of precipitation. However, as we have not utilized the incidence of precipitation in the dispersion model, the details of this computation are presented in Appendix C.4. Precipitation is discussed further in Chapter 5.

After weather, the next factor examined was aircraft type. Out of the total accident data base (not restricted to those involving fire or explosion) there were 225 accidents involving U.S. air carriers. Total operations were not available for foreign air carriers in the U.S. Based on FAA statistics for total operations, we obtained the following frequencies of accidents for large, medium, and small jets:

- Large - 14 out of 2.2 million operations
- Medium - 80 out of 35.4 million operations
- Small - 37 out of 27.7 million operations
- Total Jet
Accidents - 131 out of 65.2 million operations

Initially, it would appear that three separate accident rates should be utilized. For Jumbo Jets, however, it should be noted that substantial damage accidents are determined on the basis of a dollar threshold and that, therefore, a substantial damage accident for a large jet might be more likely than for a medium or small jet, since even minor accidents might be quite costly. This theory is corroborated by the fact that the proportion of substantial damage accidents is much higher for large jets than for medium and small jets. Indeed, the total destruction accident rate for large jets is no larger than for medium jets. (In addition, there were 5 accidents in the first two years of operation for large jets, and a relatively small number of operations. When these accidents are subtracted, there is not a significant difference between large jets and medium and small jets.) In view of these considerations, we did not treat large jets differently from medium jets. Although there was some rationale and some statistical evidence for treating medium jets and small jets separately, the difference between the two classes is not substantial and, more importantly, there is a great deal of uncertainty in the future mix of medium and small jets. Within the accident probability model, we therefore assumed a single accident rate for all three classes of aircraft.

Operational phase and type of accident were considered concurrently. The damage classification and operational phase probabilities were based on the accident record of the 81 fire and explosion accidents. The probability of the type of release (plume or explosive) was based on our judgement after we made a careful examination of detailed accident reports.

The 81 fire and explosion accidents in the data base were broken down into the following categories:

	<u>Total Destruction</u>	<u>Substantial Damage</u>	
Take-Off	13	7	20
Landing	31	6	87
Cruise	9	4	13
Static or Taxi	3	8	11

(As noted previously, we have aggregated accidents caused by fire and explosion with those involving fire after impact because we did not feel that these two classifications were sufficiently different in terms of carbon fiber release.)

The corresponding conditional probabilities consistent with these frequencies are:

	<u>Total Destruction</u>	<u>Substantial Damage</u>
Take-Off	.16	.09
Landing	.38	.07
Cruise	.11	.05
Static or Taxi	.04	.10

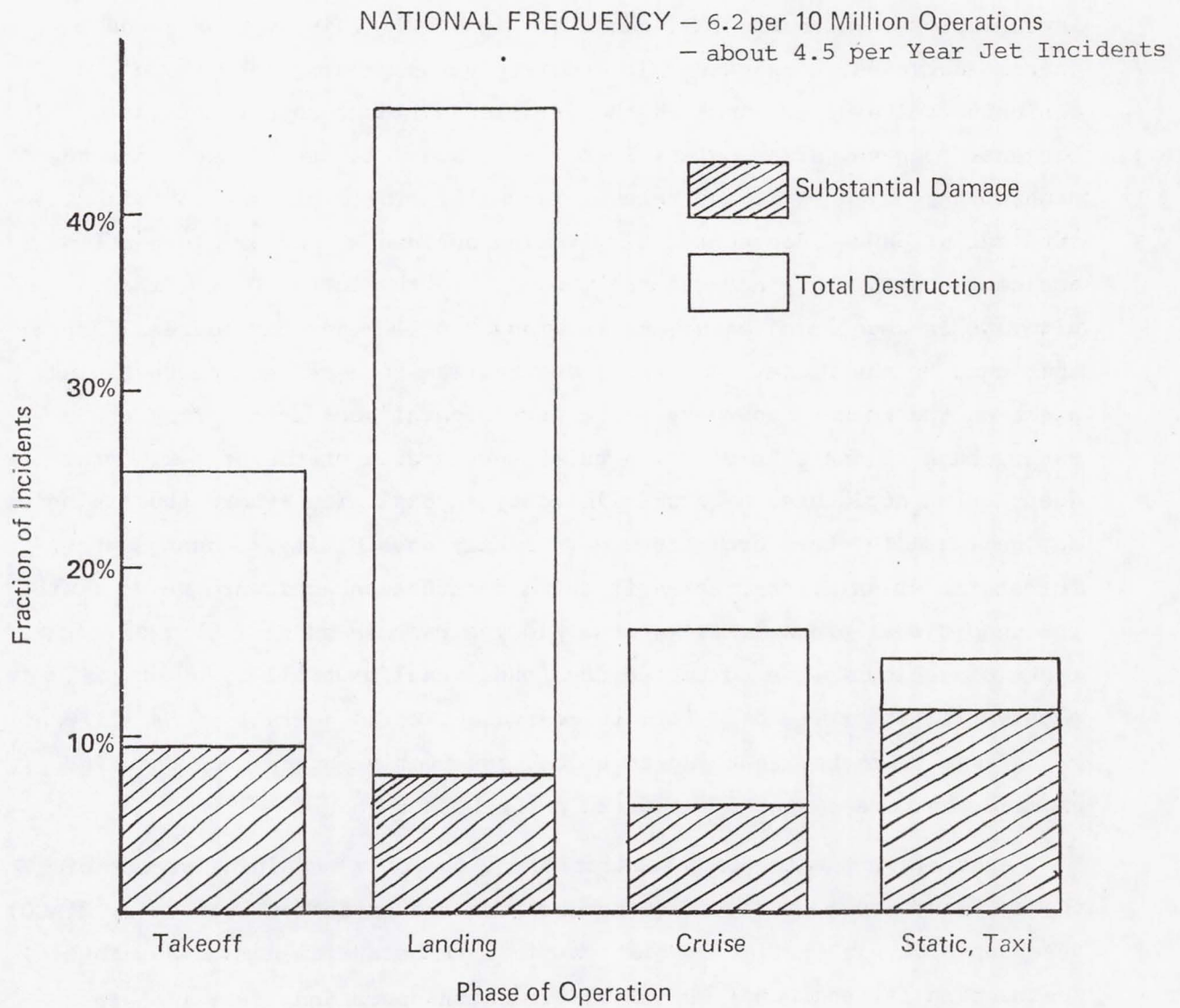
Thus, for example, there is 38% chance that a fire accident is a total destruction landing accident. As noted previously, both the operational phase and the degree of damage are important variables in the risk simulation. These conditional probabilities are depicted in the bar chart of Figure 4-1. In examining the figure, recall the average of 4.5 jet accidents per year derived earlier.

For the analysis of individual city airports, we did not incorporate cruise accidents since all accidents were assumed to be takeoff, landing or static/taxi. The respective probabilities of these events were simply conditional probabilities arising from the previous accident frequency tables. These probabilities are:

	<u>Total Destruction</u>	<u>Substantial Damage</u>
Take-Off	.191	.103
Landing	.456	.088
Static or Taxi	.044	.118

FIGURE 4-1

DOMESTIC AIR CARRIER INCIDENTS WITH FIRE AND/OR EXPLOSION



Source: NTSB Accident/Incident Statistics, 1968-1976

The aspect of the model for which we did not have a statistical basis was the fraction of accidents giving rise to an explosive release versus a plume release. In certain types of accidents, there is a burn period which melts the epoxy in the carbon fiber composite, followed by a delayed explosion when the fuel tanks are ignited. This type of scenario causes an explosive release. In order to assess the probability of an explosive release, we examined the detailed accident reports of the National Transportation Safety Board. For most classes of accidents the probability of an explosive release is small. These classes include all substantial damage accidents, all landing accidents, and all take-off accidents that take place off the runway. In the latter cases, the aircraft is usually airborne and the impact will generally cause a fire that engulfs the plane. For total destruction take-off accidents taking place on the runway, however, there were several accidents during the early phase of the take-off. In this case, and in static or taxi total destruction accidents, a burn followed by an explosion (where the explosion may be caused by the burn) is a more likely possibility. Consequently, for static or on-airport take-off total destruction accidents we estimated the conditional probability of an explosive release as 25%. For all other types of accidents, we estimated the conditional probability of an explosive release to be 5%. This is equivalent to an overall probability of 9%. These estimates were judged to be conservative based upon detailed examination of eyewitness accounts in the NTSB records.

Apart from the location distribution, the only remaining aspect of the accident model is the frequency of fire and explosion accidents, $P(ACC)$. Based on U.S. air carrier statistics of 131 substantial damage and total destruction jet accidents out of 65.2 million operations from 1968 to 1976 and on the observed frequency of 81 fire and explosion accidents out of 261 substantial damage and total destruction accidents in our data base, the overall probability of a total destruction or substantial damage fire and explosion accident is:

$$\begin{aligned}
P(\text{ACC}) &= \frac{\text{No. of SD + TD accidents of U.S. jets}}{\text{No. of operations of U.S. jets}} \\
&\times \frac{\text{No. of SD + TD fire/explosion accidents}}{\text{No. of SD + TD accidents}} \\
&= \frac{131}{65.3 \times 10^6} \times \left(\frac{81}{261} \right)^* = 6.23 \times 10^{-7}.
\end{aligned}$$

Note that the rate is based on both the rate of jet accidents of any type and the proportion of fire and explosion accidents for all types of craft.

Based on the equation (4-1) we also have:

$$P(\text{ACC}_i) = 2.8 \times 10^{-6} P(\text{IFR}_i) + 3.6 \times 10^{-7} P(\text{VFR}_i)$$

This implies that the probability of an accident in IFR weather or below and in VFR weather is 2.8×10^{-6} and 3.6×10^{-7} per operation respectively. In our use of the model, the important figures were the overall accident rates and the city multipliers implicit in equation (4-1). The multipliers were used in determining where an accident occurred, given an accident somewhere in the U.S.

For any given airport, we did not include cruise accidents. Hence, the probability of an accident other than cruise is:

$$\begin{aligned}
&\frac{\text{No. of SD + TD accidents of U.S. jets}}{\text{No. of operations of U.S. jets}} \times \frac{\text{No. fire/explosion SD + TD non-cruise accidents}}{\text{No. of SD + TD accidents}} \\
&= \frac{131}{65.3 \times 10^6} \times \frac{68}{261} = 5.23 \times 10^{-7} \text{ per operation}
\end{aligned}$$

Also, $P(\text{ACC}_i) = 3.03 \times 10^{-7} P(\text{VFR}_i) + 2.36 \times 10^{-6} P(\text{IFR}_i)$. That is the probability of an accident other than a cruise accident is 3.03×10^{-7} and 2.36×10^{-6} per operation in VFR and IFR weather, respectively.

*These values (81 and 261) are for all aircraft types, not only jet aircraft. The calculation thus implicitly assumes that fire and explosion have the same likelihood for all aircraft types.

4.5 ACCIDENT LOCATION MODEL

The final step in the accident probability analysis was the determination of the probability distribution function of distance and angle for each class of accident. For static accidents, we assumed that the accident was located close to the terminal area. For takeoff and landing accidents, we utilized the data base to determine the probability distribution for distance from the end of the runway, as recorded by NTSB. In the latter category, for accidents on the airport we developed a distribution of accident locations on the airport. For off-airport accidents, the distance from the airport center was assumed to be approximately 1.6 km. (1 mile) more than the distance from the end of the runway. This assumption is based on the fact that most runways are approximately 3 km. long and that the midpoints of multiple runways are not separated by large distances. This is not an unreasonable assumption for the airports analyzed.

The angle of the accident relative to the airport is the sum of two angles: the orientation of the runway and the angle from the runway. To compute the orientation of the runway we compiled usage statistics for the runway of each of the airports that we were interested in. For take-off accidents we assumed that the accident takes place closest to the take-off end of the runway. For landing accidents we determined from our accident data base that landing accidents taking place off the runway are approximately evenly split between undershoots and overshoots. Hence, landing accident probabilities were split equally between the angle corresponding to the near edge of the runway and the far edge of the runway. These assumptions were used in conjunction with runway usage statistics for each of the major airports to construct a probability distribution for angle from the runway.

The distance dependency relationship was split into three cases: total destruction landing, total destruction take-off, and substantial damage. (There are only 13 substantial damage accidents involving a take-off or landing and we did not judge 13 cases to be statistically sufficient to separate the two substantial damage cases.) For each of these cases, the functional form of the distance relationship was assumed to be:

$$\text{Pr}(\text{Distance} > r) = Ae^{-\lambda r}$$

A is the empirically observed frequency of off-runway accidents, adjusted to account for the truncation of accidents occurring beyond 5 miles (8 km.). The assumed exponential form of the off-runway accident location distribution has been used by ADL and other investigators in the past, and has resulted in good fits of the data. The model assumes that the likelihood of an accident at a given distance from an airport divided by the likelihood of an accident at any distance greater than or equal to that distance is a constant. That is:

$$\frac{\text{Prob (Accident at } r)}{\text{Prob (Accident at distance } r)} = \text{constant}$$

The quantity to the left is known as the hazard function and a constant hazard function is both intuitively appealing and historically accurate. The coefficient λ can be solved for by the following maximum likelihood equation:

$$\frac{1}{\lambda} - \frac{5e^{-5\lambda}}{1 - e^{-5\lambda}} = \frac{\sum X_i}{n}$$

where

n = number of off airport accidents

X_i = distance from runway of i th accident

(The unusual form of this equation is due to the fact that the distribution truncates accidents located more than 5 miles (8 km.) from the edge of the runway. Such cruise accidents do not generally conform to the exponential fit.) For the three different cases, we obtained the following distributions:*

Substantial Damage

$$\text{Pr}(\text{Distance} > r) = .12e^{-.94r}$$

Total Destruction Landing

$$\text{Pr}(\text{Distance} > r) = .452e^{-.43r}$$

Total Destruction Take-off

$$P(\text{Distance} > r) = .246e^{-.43r}$$

Take-off and landing distributions for total destruction accidents were based on fire and explosion accidents only. The distribution for substantial damage accidents was derived from all substantial damage accidents (i.e., not only those characterized by fire or explosion). There was no statistical basis for separating take-off and landing substantial damage accidents. In addition, the exponential fall-off factor for total destruction accidents was assumed to be the same for both take-off and landing. (The difference in these categories was in the frequency of off-runway accidents.)

After these distributions were constructed, they were tested using a goodness of fit test. The chi-squared values for the substantial damage and total destruction accidents were 4.6 and 7.89, respectively. Both cases involved seven degrees of freedom and were, hence, within acceptable bounds. (The 95% limits for 7 degrees of freedom is 14.07). For total destruction accidents we also tested a hypothesis that takeoff and landing locations could be drawn from the same distribution. Aggre-

*For convenience these are expressed in miles rather than kilometers, as is the practice in the U.S.

gating the entire distribution was not statistically valid; however, in comparing the cell frequencies of off-airport accidents for takeoffs and landings involving total destruction, there was no significant difference. For this reason, the exponential constants were assumed to be the same. (It should be noted that there were only a small number of total destruction off-runway accidents. Much of the aggregation in our models was due to the limitations of the data.) The tables used to develop these tests are presented in Appendix C.

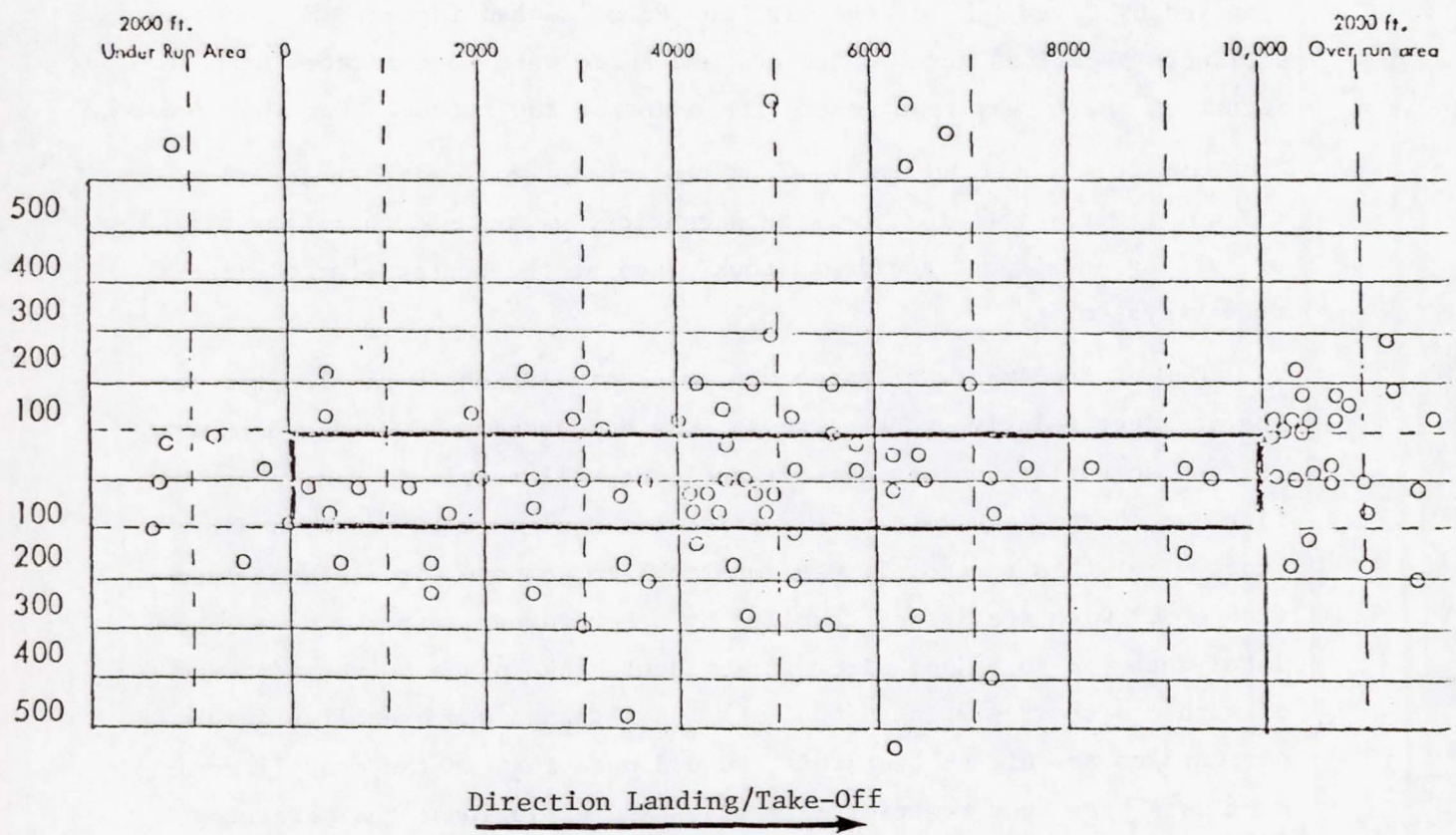
Our model also required an accident location in the event of an on-airport accident. Figure 4-2 presents a scatter diagram of accidents compiled by Hewes [1] of the Air Line Pilot's Association. For on-runway accidents locations were scattered, and there were more located near the center of the runway than toward the edges of the runway. For this reason, for simplicity, and due to the fact that the precise airport location did not greatly affect dispersion scenarios, we assumed that take-off or landing on-airport accidents took place at the center of the airport runway system.

One of the important aspects of risk simulation is the location of the accident relative to the runway. As discussed in Chapter 5 on release scenarios, an off-airport accident will result in a more severe fire due to the inability of fire-fighting equipment to reach an aircraft. For this reason, it was important to compare our distance location model with statistics compiled by other investigators. Hewes has noted that 75% to 85% of aircraft accidents take place on the airport or within a short distance (6000 m.). Although our overall off-runway percentages are higher than this, we did note that in the overall accident data base (not restricted to fires and explosions) the percentage of on-airport accidents was higher and approximately equal to the Hewes figures. Nash has noted that the frequency of on-airport accidents for fire accidents is lower than for the total set of accidents. Nash noted a figure of 69% of fire accidents being located on or close to the runway. This statistic was based on British accident data.

FIGURE 4-2

SCATTER DIAGRAM OF ACCIDENT LOCATIONS COMPILED BY
HEWES FOR AIR CARRIER ACCIDENTS 1964 - 1965

Air Line Pilots Association - August 30, 1975



The final aspect of the model is the angle from the runway. Data on angles were reported only irregularly in NTSB accident data. Consequently, we utilized two other sources and constructed a limited sample of our own data based on general aviation accidents as well as air carrier accidents. (This sample consisted of about 40 accidents.) The other sources of data were Pickard and Low Associates [5] and the scatter diagram compiled by Hewes depicted in Figure 4.2. All three sources indicate a low average angle (all 13° or below) even when the data are restricted to the set of accidents with non-zero angles. Our own sample and also the Hewes data showed a moderate negative correlation with distance from the end of the runway. We utilized a correlation of -20% together with the exponential fit developed by Pickard and Low. Their equation for the probability that the angle is greater than θ_o is given in the following expression:

$$P(\theta > \theta_o) = .78 e^{-\theta/55} \quad 0 \leq \theta \leq 90^\circ$$

We made an additional adjustment in the Pickard and Low equation, since their distribution was for the angle relative to the edge of the runway, and we were interested in the distribution relative to the center of the runway. The angle relative to the center of the runway will always be slightly less than the angle relative to the edge of the runway. By assuming an average middle to end of runway distance of 1.6 km. (1 mile) and a typical off-runway distance of 3.2 km. (2 miles) one can see geometrically that the angle relative to the center of runway is approximately two thirds of the angle relative to the edge of the runway. We therefore assumed an exponential distribution whose mean angle for off-runway accidents was $2/3$ of the mean angle utilized by Pickard and Low. Hence, the final distribution assumed for angle relative to the center of the runway was $.78e^{-\theta/3.7}$. Although this is a rough approximation, it should be noted that the angle from the runway is not a significant variable in the overall risk simulation.

4.6 SUMMARY AND DISCUSSION

The results obtained in the previous sections may be summarized as follows:

- Probability of a fire or explosion accident per operation

Overall	6.23×10^{-7}
IFR	2.8×10^{-6}
VFR	3.6×10^{-7}

- Probability of a non-cruise fire or explosion accident per operation

Overall	5.23×10^{-7}
IFR	2.36×10^{-6}
VFR	3.03×10^{-7}

- Conditional Probability of Accident Type

	<u>Total Destruction</u>	<u>Substantial Damage</u>
Take-Off	.16	.09
Landing	.38	.07
Cruise	.11	.05
Static or Taxi	.04	.1

- Conditional Probability of Explosive Release

Static or Take-off on Airport or Taxi involving total destruction:	0.25
Others	0.05

- Distance from edge of runway (Take-off or landing in miles)

$$P(\text{DIST} \geq R) = \begin{cases} .12 e^{-.94R} & \text{For Substantial Damage} \\ .246 e^{-.43R} & \text{Take-off Total Destruction} \\ .452 e^{-.43R} & \text{Landing Total Destruction} \end{cases}$$

- Distance from center of runway

If off-airport, one mile greater than from edge of runway.
If on-airport, zero.

- Angle from runway with respect to center of airport

$$P(\text{ANGLE} \geq \theta) = .78 e^{-\theta/3.7}$$

-20% Correlation with distance from edge of runway

There is some discussion necessary with respect to two types of sensitivities of this model. The first issue is whether the model is an accurate probabilistic interpretation of the data. The second issue, is whether there are significant changes occurring in aircraft or airport safety.

As to the accuracy of the model, there are certain aspects that are extremely accurate and other aspects that are subject to some uncertainty. We have examined an enormous number of aircraft operations over a nine year period and have observed 81 fire and explosion accidents. Assuming that the number of accidents during the period is a Poisson random variable, then the variance of the number of accidents is equal to the mean. By using the normal approximation to the Poisson, 95% confidence bounds can be found by the equations.

$$\text{Lower bound} + 1.96 \sqrt{\text{lower bound}} = 81$$

$$\text{Upper bound} - 1.96 \sqrt{\text{upper bound}} = 81$$

where 1.96 represents the number of standard deviations corresponding to a 95% confidence bound for a normal distribution. The resulting confidence bounds are 65 to 101. Thus, there is not a great deal of uncertainty in the overall accident rates.

Other aspects of the model show similar ranges of uncertainty. For example, of the 81 fire and explosion accidents 31 were takeoff total destruction. The number of takeoff total destruction accidents is estimated as a binomial. The standard deviation for the proportion of events that are binomially distributed with parameter p is:

$$\sqrt{\frac{p(1-p)}{N}}$$

where N is the number of observations (181 in this case). Again, using the normal approximation, the 95% confidence limits are solved by the system of equations:

$$p_{\text{lower}} + 1.96 \sqrt{\frac{p_{\text{lower}}(1-p_{\text{lower}})}{81}} = \frac{31}{81}$$

$$P_{\text{upper}} - 1.96 \sqrt{\frac{P_{\text{upper}}(1-P_{\text{upper}})}{81}} = \frac{31}{81}$$

where P_{upper} and p_{lower} represent the upper and lower confidence bounds respectively. The solution to the equations is the interval 28% to 49%. This is a relatively wider confidence bound than that for the overall accident rate; however, the overall risk profile is expected to be more sensitive to the overall accident rate than to the conditional probability of the operational phase and severity type. (This was corroborated by the sensitivity runs discussed in Chapter 10). The distance distribution, being based on a limited number of samples, may be subject to some uncertainty but does not have much impact on the overall risk profile, due to the typically large dispersion radii.

One aspect of the model that may show some sensitivity with respect to the national risk profile and be subject to some uncertainty is the probability of an explosive type release. As discussed in the next chapter, this probability was based on judgmental considerations rather than hard data. Furthermore, maximum exposure levels in any metropolitan area are affected by this type of release. Because we were not able to determine with great accuracy the probability of an explosive release, we strove to utilize a conservative value for the probability.

The second issue noted above is improvements in safety. Accident rates have apparently been decreasing slightly over the years. We have, however, chosen a conservative approach by directly utilizing the accident rate over the nine year period 1968-1976. The risk profiles are not very sensitive to small reductions in the accident rate.

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5. CARBON FIBER RELEASE CONDITIONS

5.1 INTRODUCTION

This chapter presents the methodology and data sources analyzed to determine the carbon fiber release scenarios for aircraft accidents. The scenarios consisted of a set of probability distributions for each of the variables judged to have impact on carbon fiber dispersion and economic loss. Most of the distributions were independent of each other, but some were correlated. The set of probability distributions for all of the variables considered was used as input to the risk simulation model that is to be discussed in Chapter 10. Because of this simulation approach we did not identify unique scenarios that encompassed a whole set of variables; rather, the emphasis was on a distribution for each individual variable.

In a general sense, a release scenario consisted of all the variables that could possibly affect dispersion. These include, of course, such accident variables as severity of damage and phase of operations. The focus of this chapter, however, is on those other variables not incorporated within the accident model. These variables include all of the weather variables as well as such variables as fuel burned and carbon fibers released. There is a close relationship between some of these variables and the accident type, and this will be discussed below.

A release scenario was developed under the implicit assumption that an accident had occurred. The simulation model actually simulated individual accidents and hence produced a conditional distribution of losses given an accident. This conditional distribution was then combined with the probability of an accident in order to develop unconditional distributions of loss; this is discussed in Chapter 11. Thus, it should be recognized that release variables are conditional on an accident, and that all variables presented in this chapter are conditional variables.

5.2 VARIABLES INCORPORATED IN RELEASE CONDITION MODELS

There were three types of probabilistic variables incorporated into the simulation model. These were:

1. Accident variables such as location, phase of operation and severity of damage.
2. Aircraft variables such as fuel burned and carbon fibers released that indirectly depended on the accident model.
3. Weather variables.

The accident variables include:

1. Phase of operation and severity.
2. Type of release.
3. Location from center of runway.
4. Angle from runway.
5. Orientation of runway.

The distributions for some of these variables were presented in the previous chapter on accident probabilities. The first two variables deal with the type of accident and are very closely related to the second set of variables, the aircraft variables. The third, fourth, and fifth variables are all location variables and result in a simple geometric adjustment of the dispersion cloud. All five variables were discussed in the accident probability model and the distributions for all except orientation of runway were presented in Chapter 4.

Orientation of the runway was a city-dependent variable. The orientation of the runway together with the angle from the runway determined the angle of the accident. For cases where the accident was off the airport, the location of the accident would depend on this angle. We obtained this distribution by taking each city's runway usage frequencies and adjusting these frequencies to account for the fact that approximately half of landing accidents are undershoots and half are overshoots. For the Boston airport, we obtained runway frequency usages directly from the Massachusetts Port Authority [14]. For 17 cities usage statistics were obtained from the report Airport Noise Reduction Forecast [1]. For seven additional cities, we assumed a uniform distribution of usage among the known runway orientations. For one city (Las Vegas), we assumed a uniform distribution of runway

orientation and usage, since we did not obtain the data on Las Vegas runways in time to complete the simulation. The runway orientation distributions for all cities appear in Appendix G.

In the two sections that follow, we discuss each of the other two sets of variables, aircraft variables and weather variables. Weather variables include:

1. Wind Direction
2. Wind Velocity
3. Stability Class
4. Ambient Temperature
5. Precipitation

The aircraft variables include:

1. Type of Aircraft
2. Fuel Burned
3. Carbon Fibers Released
4. Duration of Burn

As noted, the existence of an explosive or plume release had a great impact on the release scenarios. The probability of an explosive type of release is the only aspect of the accident probability model that could not be empirically corroborated, due to the inadequate historical data.

5.3 AIRCRAFT VARIABLES

This section describes the use of each of the aircraft variables.

Aircraft Type

According to airframe manufacturers' predictions [2], the jet fleet mix in 1993 will consist of 25% small jets, 60% medium jets, and 15% large jets. (Existing aircraft in each class are described in the chapter on accident probabilities.) This is based on the assumption that the new Boeing 757 and 767 will be part of the medium jet category. Of these types of planes, it was projected that 50% of small and large jets will utilize carbon fibers and 60% of medium jets will utilize carbon fibers. The predicted fleet mix is almost identical to today's fleet mix. We consequently made the assumption that the operations mix at any given airport will be the same as it is today. Thus, the probability of a given aircraft type being involved in an accident at any airport was obtained from the mixture of operations at that airport today.

The only adjustment in this procedure was due to the fact that in 1993 the different size classes will have different carbon fiber utilization. The model assumed not only that there was an accident involving a jet in a substantial damage or total destruction fire accident, but also that the plane involved utilized carbon fibers. We thus weighted today's operations mixture at each airport by 50%, 60%, and 50%, respectively, for small, medium, and large jets. The effect of this adjustment was to increase the conditional probability of a medium jet being involved in a given accident.

To determine the operations mix for domestic airlines at each U.S. airport, we used the F.A.A. publication Airport Activity Statistics [3]. We then examined an international flights schedule publication [4] to estimate the approximate number of foreign airline operations for each aircraft size and each airport. The resulting conditional probabilities for each aircraft type at each airport are presented in Appendix G.

Fuel Burned

The amount of fuel burned is dependent on the accident type, being larger for total destruction, as well as for the takeoff phase. An accident location off-the-runway at a distance greater than 600 meters from the edge of the runway results in the inability of firefighting equipment to reach the craft; for this case the fuel burned was hence larger. Fuel burned also depends on aircraft type; the larger the plane, the greater the fuel burned. The average fuel load for different aircraft and for different operational phases was determined from Jane's [5] and other sources [6]. For off-airport accidents, we assumed that 100% of the fuel was consumed in the case of total destruction and 20% in the case of substantial damage. For on-airport accidents, which are normally controlled by fire crews, we assumed that the fuel consumed will be 1/3 of the corresponding off-airport amount. The amount of fuel for each of these cases is presented in Appendix G.

Carbon Fibers Released

The mass of fibers released depends on accident type, accident location, and aircraft type in an analogous manner to fuel burned. The total amount

on board was estimated by aircraft type using forecasts of average carbon fiber utilization, fleet mix, and aircraft weight. The fraction released was assumed to depend upon accident type, as explained below.

In 1993 it is anticipated that small, medium, and large jets will utilize 500 kg, 700 kg, and 2,000 kg of carbon fibers in composites respectively (for those aircraft that utilize CF.) In terms of weight, about 70% of the composite consists of carbon fiber. For explosive type releases it was assumed that 25% of the carbon fibers would be released in the case of total destruction and that 10% of the carbon fibers would be released in the case of substantial damage. In the case of a plume release, it was assumed that an off-airport, total destruction accident would result in 20% of the carbon fibers being released. For on-the-airport accidents we assumed that the carbon fibers released would be one-half of the corresponding off-airport amount and, that in the case of a substantial damage accident the amount released would be one-half of the total destruction amount. The masses of carbon fibers released for all of these combinations are presented in Appendix G.

The above estimates of CF mass released are based upon the results of the burn tests conducted at Dahlgren Labs, which were described in Section 2.2. However, they must be considered tentative estimates, since the chamber tests are not representative of real-world conditions. For one thing, even if an aircraft carrying CF were involved in a fire, the CF might be unaffected by the flames. Moreover, there is still doubt about the ability of a fire to dislodge such a large fraction of the CF in the form of single fibers, and ongoing outdoor tests are investigating this assumption. In the meantime the CF release estimates were made as high as realistically possible, in order to yield a conservative risk assessment.

Duration of Burn

We assumed that a fire off-airport would last for 30 minutes in the case of total destruction and 12 minutes in the case of substantial damage. A fire on-airport is expected to be extinguished by fire crews within 4 minutes, according to informed sources [7]. Although a total destruction fire may last longer, we conservatively assumed an intense release of fibers over a short interval.

A summary of the parameters cited above is presented in Table 5-1.

TABLE 5-1
RELEASE SCENARIO ASSUMPTIONS

Accident/Incident Description	Percent of Carbon Fibers Released		Percent of Fuel Burned*	Duration*
	Fire	Fire and Explosion		
On Airport Total Destruction	10%	25%	33%	4 min.
Off Airport Total Destruction	20%	25%	100%	30 min.
On Airport Substantial Damage	5%	10%	6.7%	4 min.
Off Airport Substantial Damage	10%	10%	20%	12 min.

* Source: ALPA, Massport

5.4 WEATHER VARIABLES

For the accident probability model one of the variables associated with an accident is the weather classification (IFR - VFR). Given that an accident occurred, the dispersion calculation required the following five variables:

- Wind Velocity
- Wind Direction
- Pasquill Stability Class
- Temperature
- Precipitation

In addition the dispersion routine computed the adiabatic lapse rate as a function of stability class. The interactions between these variables and the IFR/VFR condition were exceedingly complex, and varied from one city to another. Due to the uncertainties inherent in the model as a whole, we concluded that there would be no significant loss of accuracy in assuming independence between IFR/VFR and these other variables, except for precipitation. (Even in the case of precipitation, although we could calculate the probability of precipitation at the time of the accident, we could not utilize it effectively in the dispersion analysis.) The carbon fiber clouds would normally travel over many kilometers for a period of hours, during which weather conditions would undoubtedly fluctuate. However, the dispersion model assumed constant weather conditions. Hence, the IFR/VFR condition at the time of the accident would have only a slight relationship to the overall weather pattern affecting the CF dispersion, and the assumption of independence may yield a more realistic prediction of average weather conditions during dispersion.

As a result of the assumption of IFR/VFR being independent of other weather variables, we used IFR/VFR only in the calculation of the conditional probability of an accident taking place at a given airport. In other words, if a city had a higher proportion of IFR weather, we adjusted the conditional probability of an accident taking place at that airport upward. The details of this adjustment are explained in the section on the national risk profile (Chapter 11).

A discussion of each of the weather variables is presented below:

Stability Class

This variable could take on six possible values, ranging from stable through neutral to unstable. We obtained the probabilities of each class

for each airport from the airport Climatological Summaries published by the Department of Commerce [8].

Wind Velocity

This variable was drawn from a frequency distribution which was dependent on the stability class. The data for wind velocity were also drawn from the airport Climatological Summaries. To simulate the bi-variate distribution, the model utilized a complete series of speed distributions, each distribution corresponding to a specific stability class. Matrices presenting these series of distributions for each city simulated are presented in Appendix G.

Wind Direction

This variable was drawn from a wind rose giving frequencies of wind in various directions. These distributions are also presented in Appendix G. For each city simulated we generated the correlation coefficient between wind speed and wind direction. Many of these cases were small (below 5%) but for other cities there was moderate correlation between the two variables. For these cases, we ourselves correlated the speed and the direction in the simulation model.

Temperature

This variable was drawn from a frequency distribution and was independent of the other variables. Frequency distributions were generated from data in the U.S. Statistical Abstracts [9] for low and high average temperatures in each month of year for each city, together with lowest and highest temperatures ever recorded. The ambient temperature was required as an input to the dispersion calculations.

Precipitation (Rain, etc.)

This variable consisted of a "yes-no" indicator, and the probability of a "yes" condition was dependent upon the IFR/VFR frequencies at the airport in question. The reason for this was that rain is generally more probable in IFR conditions than in VFR conditions. Since IFR/VFR splits vary by city, and are different given an accident than for an unconditional situation, the probability of rain given an accident can be computed from an application of conditional probability, as shown in Appendix C.4.

The probability of rain given an accident with fire is different from both (a) the unconditional probability of rain, and (b) the probability of rain given an accident of any type. For Boston, for example, the probability of rain given an accident is .409 which is much greater than the unconditional probability of rain, namely .21. In fact, the frequency of IFR accidents was higher for fire accidents than for all types of accidents combined, and hence the probability of precipitation for fire accidents was higher than for other accidents. However, due to the complexity of implementing a model that incorporated the existence of precipitation and due to our conservative philosophy in determining a loss distribution, we did not implement a precipitation factor within the dispersion model. If precipitation did occur, it would tend to wash out the airborne fibers and hence reduce the exposure in the area covered. Thus, the suppression of this effect may be considered as an additional conservative assumption in the computation of a risk profile. Ignoring the presence of rain would lead to an exaggeration of the risk by at most 40% (which is approximately the national probability of rain given an accident), even if there were a total washout in rain.

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6. CARBON FIBER DISPERSION MODELS USED FOR RISK ANALYSIS CALCULATIONS

6.1 INTRODUCTION

For evaluating the downwind, ground level exposure contours from carbon fiber dispersion, we have chosen two fiber release scenarios. The first is the "fire and explosion release" in which all of the fibers are released instantaneously. This model applies to accident scenarios where an explosion follows a short-duration fire in the aftermath of the accident. The second is the "plume release" scenario in which the total mass of fibers is released into a fire plume. This model applies to aircraft accidents where only a fire results. These models are described in detail below. Substantial additional detail is presented in Appendix D. The nomenclature is presented in Section D.5 of Appendix D.

6.2 FIRE-EXPLOSION RELEASE MODEL

In formulating the model we have made the following assumptions:

- The release is instantaneous,
- The release is from a point source near ground level,
- The velocity of the wind is constant in time and in direction,
- The wind velocity variation from the ground level up is taken into account by using a mean wind speed, and
- Re-entrainment of any settled fibers into the dispersing cloud is negligible.

The concentration at any point downwind is given by:

$$C(x, y, z, t) = \frac{M(x_c)}{(2\pi)^{3/2} \sigma_y^2(x_c) \sigma_z(x_c)} \exp \left[-\frac{(x-x_c)^2 + y^2}{2\sigma_y^2} \right] \times \left\{ \exp \left[-\frac{(z-h)^2}{2\sigma_z^2} \right] + \exp \left[-\frac{(z+h)^2}{2\sigma_z^2} \right] \right\} \quad (6.1)$$

where,

- $M(x_c)$ = mass of carbon fibers present in the entire cloud
when the center of the cloud is at a downwind
distance of x_c
- $\sigma_y(x_c)$ = y direction dispersion parameter,
- $\sigma_z(x_c)$ = z direction dispersion parameter,
- x = downwind distance
- y = crosswind distance
- z = distance above ground, and
- h = height above ground at which the fibers are released
into the atmosphere.

The location x_c of the cloud center is given by:

$$x_c = u_w t \quad (6.2)$$

The mass $M(x_c)$ at any instant is less than the mass M_o released initially because of particle settling onto the ground. The relationship between M_o and $M(x_c)$ is given by:

$$M(x_c) = M_o p(x_c) \quad (6.3)$$

where $p(x_c)$ is called the depletion function given in Equation 10 of Appendix D. The numerical value of $p(x_c)$ depends upon the settling velocity, wind velocity, release height, and the atmospheric stability in addition to x_c .

The depletion function curves shown in Figure D-7 were fit with second-degree equations and the resulting expressions were used in our calculations.

The exposure^{*} at any point (x, y, z) is calculated by using the following:

$$D(x, y, z) = \int_{t=0}^{\infty} C(x, y, z, t) dt \quad (6.4)$$

Substituting equation 6.1 into equation 6.3 and writing:

$$dx_c = u_w dt \quad (6.5)$$

we can show that equation 6.4 can be represented with a high degree of accuracy by:

$$D(x, y, z) \simeq \frac{M_o p(x)}{2\pi\sigma_y\sigma_z u_w} \left[1 + \operatorname{erf} \left(\frac{x}{\sqrt{2}\sigma_y} \right) \right] \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left[\frac{\exp\left\{-\frac{(z-h)^2}{2\sigma_z^2}\right\} + \exp\left\{-\frac{(z+h)^2}{2\sigma_z^2}\right\}}{2} \right] \quad (6.6)$$

From the previous equation, we obtain the maximum exposure at ground level. This is given by:

$$D_{\max} \simeq \frac{M_o p(x)}{2\pi\sigma_y\sigma_z u_w} \left[1 + \operatorname{erf} \left(\frac{x}{\sqrt{2}\sigma_y} \right) \right] \exp\left(-\frac{h^2}{2\sigma_z^2}\right) \quad (6.7)$$

*Throughout this report the terms exposure and dosage are utilized interchangeably to represent a time integrated concentration of carbon fibers.

The semi-width at ground at a given downwind position x for a given exposure value D^* can then be determined by:

$$SW(x) = \sigma_y(x) \sqrt{2 \ln (D_{max}/D^*)} \quad (6.8)$$

The above equations have been computerized for ease of calculation in the risk analysis investigation.

6.3 RESULTS FOR FIRE FOLLOWED BY EXPLOSION DISPERSION MODEL

Representative results obtained from a parametric study are illustrated in Table 6-1. The parametric study included the variation of:

- Mass of fibers released
- Height above ground of the fiber source
- Atmospheric stability type
- Wind speed

The fibers were all assumed to be single fibers of uniform size with terminal velocity of settling equal to 0.032 m/s. Also it was assumed that the total number of individual fibers per kg of release was 10^9 . The Pasquill dispersion parameter values were used (Figures D-3a and D-3b).

The results indicate that the downwind distance to a given ground exposure increases as the exposure level of concern decreases. Also as the height of release increases the downwind distance and the exposure areas increase.

One peculiar result noticed is that, contrary to expectations, dispersion under stable weather does not represent the worst condition from the point of view of equipment vulnerability. In fact, it can be seen from Table 6-1 that for exposure values less than 10^5 F-s/m³, the hazard distance downwind is larger in neutral atmosphere (D) than in stable atmosphere (F). The reason for this anomalous result is simple. In the case of F weather (which is generally associated with low wind

TABLE 6-1(a)

REPRESENTATIVE RESULTS FOR CARBON FIBER RELEASE IN FIRE-EXPLOSIVE MODE

Type of Atmos phere	Wind Velo city (M/S)	Mass Rel- eased (KG)	Height of Source (M)	Nearest point of contour, NEAR,(M); Farthest downwind travel distance, FAR,(F); Maximum width, WMAX,(M); and area within contour, AREA,(M ²); for different exposure values.															
				1.0E6 FS/M ³				1.0E5 FS/M ³				1.0E4 FS/M ³				1.0E3 FS/M ³			
				NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA
3	5	50	0	50		109		50		328		50		967		50		2835	
					550		4.27E4		1850		4.64E5		6100		4.59E6		20350		4.52E7
3	5	50	10	50		116		50		368		50		1092		50		3187	
					600		5.02E4		2100		5.92E5		7000		5.96E6		23250		5.81E7
3	5	50	20	150		102		100		370		100		1117		100		3266	
					600		3.61E4		2150		5.96E5		7200		6.23E6		23900		6.10E7
3	5	100	0	50		152		50		455		50		1338		50		3885	
					800		8.92E4		2650		9.28E5		8750		9.14E6		29350		8.94E7
3	5	100	10	50		166		50		511		50		1512		50		4361	
					900		1.11E5		3050		1.20E6		10000		1.18E7		33450		1.14E8
3	5	100	20	100		159		100		519		100		1549		100		4468	
					900		9.98E4		3100		1.22E6		10300		1.24E7		34350		1.20E8
3	5	500	0	50		328		50		967		50		2835		50		8070	
					1850		4.64E5		6100		4.59E6		20350		4.52E7		68600		4.34E8
3	5	500	10	50		368		50		1092		50		3187		50		9005	
					2100		5.92E5		7000		5.96E6		23250		5.81E7		77400		5.47E8
3	5	500	20	100		370		100		1117		100		3266		50		9213	
					2150		5.96E5		7200		6.23E5		23900		6.10E7		79350		5.74E8

TABLE 6-1(b)

REPRESENTATIVE RESULTS FOR CARBON FIBER RELEASE IN FIRE-EXPLOSIVE MODE

Type of Atmosphere, Wind Velocity (M/S), Mass Released (KG), Height of Source (M), Nearest point of contour, NEAR, (M); Farthest downwind travel distance, FAR (M); Maximum width, WMAX, (M); and area within contour, AREA, (M^2); for different exposure values.

Type of Atmosphere	Wind Velocity (M/S)	Mass Released (KG)	Height of Source (M)	1.0E6 FS/ M^3				1.0E5 FS/ M^3				1.0E4 FS/ M^3				1.0E3 FS/ M^3			
				NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA
4	4	50	0	50	950	118	8.34E4	50	3350	369	9.58E5	50	11000	1115	9.59E6	50	34000	3098	8.26E7
4	4	50	10	100	1200	137	1.19E5	100	4300	455	1.50E6	50	14100	1394	1.54E7	50	43100	3828	1.29E8
4	4	50	20	200	1200	124	9.77E4	150	4600	477	1.67E6	150	15300	1494	1.78E7	100	46650	4102	1.50E8
4	4	100	0	50	1400	167	1.77E5	50	4850	518	1.95E6	50	15600	1538	1.88E7	50	46900	4135	1.52E8
4	4	100	10	100	1750	199	2.58E5	50	6150	642	3.08E6	50	20000	1915	3.00E7	50	59100	5090	2.36E8
4	4	100	20	150	1850	196	2.61E5	150	6650	681	3.48E6	100	21650	2052	3.47E7	100	63800	5449	2.73E8
4	4	500	0	50	3350	369	9.58E5	50	11000	1115	9.59E6	50	34000	3098	8.26E7	50	95900	7863	5.92E8
4	4	500	10	100	4300	455	1.50E6	50	14100	1394	1.54E7	50	43100	3828	1.29E6	50	118600	9558	8.90E8
4	4	500	20	150	4600	477	1.67E6	150	15300	1494	1.78E7	100	46650	4102	1.50E8	100	127400	10198	1.02E9

TABLE 6-1(c)

REPRESENTATIVE RESULTS FOR CARBON FIBER RELEASE IN FIRE-EXPLOSIVE MODE

Type of Atmos phere	Wind Velo city (M/S)	Mass Rel- eased (KG)	Height of Source (M)	Nearest point of contour, NEAR, (M); Farthest downwind travel distance, FAR, (M); Maximum width, WMAX, (M); and area within contour, AREA, (M ²); for different exposure values.																																
				NEAR	1.0E6 FAR	FS/M ³ WMAX	AREA	NEAR	1.0E5 FAR	FS/M ³ WMAX	AREA	NEAR	1.0E4 FAR	FS/M ³ WMAX	AREA	NEAR	1.0E3 FAR	FS/M ³ WMAX	AREA																	
6	2	50	0	50		63			850		3.94E4		50		140			2050		2.20E5		50		297			1.01E6		50		586			8700		3.98E6
6	2	50	10	150		152			2400		2.69E5		150		349			5300		1.41E6		100		688			5.32E6		100		1207			16550		1.56E7
6	2	50	20	400		172			3100		3.64E5		300		453			7050		2.40E6		250		888			8.65E6		200		1491			20150		2.34E7
6	2	100	0	50		80			1150		6.93E4		50		177			2600		3.54E5		50		367			1.56E6		50		709			10500		5.81E6
6	2	100	10	150		199			3100		4.62E5		150		434			6500		2.17E6		100		824			7.51E6		100		1394			18950		2.06E7
6	2	100	20	350		242			4150		7.23E5		250		567			8550		3.69E6		250		1053			1.20E7		200		1705			22750		3.02E7
6	2	500	0	50		140			2050		2.20E5		50		297			4400		1.01E6		50		586			3.98E6		50		1073			15750		1.32E7
6	2	500	10	150		349			5300		1.41E6		100		688			9950		5.32E6		100		1207			1.56E7		100		1897			25200		3.74E7
6	2	500	20	300		453			7050		2.40E6		250		888			12650		8.65E6		200		1491			2.34E7		200		2267			29600		5.23E7

velocities), the rate of particle deposition onto the ground is high, with the result that the mass of fibers in the dispersing cloud gets depleted rather quickly. On the other hand, in a neutral atmosphere D, the rate of mass depletion by settling is small. Hence, the downwind distance up to which high concentrations persist is large. However, in the case of unstable atmosphere C, the dilution by dispersion is large and hence the downwind travel distance is limited.

The results of Table 6-1 show that the release of the fibers from an elevated level has larger detrimental effects than release at the ground level. For example, release of 100 kg of fiber at ground level in stable (F) weather results in a ground level hazard area of $3.5 \times 10^5 \text{ m}^2$ for the 10^5 exposure level. When the same mass is released at a level of 10 m above ground, the hazard area increases to $2.2 \times 10^6 \text{ m}^2$, almost an order of magnitude increase! We also notice that this amplification effect is substantially lower in the case of C and D weathers. The principal reason for this behavior is partly due to the slow deposition of the fibers onto the ground in the case of elevated release, and partly due to the way in which the mass remaining within the cloud is distributed. A more accurate description of the settling process may reduce some of the uncertainty associated with the calculation of ground level area within a given exposure contour.

The model used is the modified Gaussian dispersion model. We recognize that the simplified approach taken and the fact that the source was not too accurately described introduce errors into the hazard area calculation. Similarly, the phenomenon of re-entrainment of settled fibers has been neglected. Inclusion of this phenomenon will increase the hazard distance. However, the single most important question to be faced is: "How accurate would the hazard area prediction be if all of the neglected phenomena were included and more accurate dispersion models were used?" While we concede that better models would provide a more accurate estimate, these models would only be as good as the data put into them. It is precisely in the input parameters (wind speed, mass released, height of release, possible partial release

at different height by fire balls, etc.) that large uncertainties exist. Therefore, for the purpose of a risk analysis calculation, we feel that the simply modified Gaussian model used is adequate.

The advantage of the model used lies in its simplicity. With very little computing effort, the results of distance to a given dosage can be easily calculated. In addition, when the probability of failure of an equipment is known as a function of exposure level (as against a "critical" dosage), the total failure probability by exposure to a certain mass of fibers released in a given weather can be determined.

In formulating the above fire-explosion scenario dispersion problem we have tacitly assumed that all of the fibers would be released at a single location. This need not always be the case. One can postulate a scenario in which an aircraft crash would result in debris being scattered over a wide area. The debris, in turn could burn in different locations, releasing carbon fibers into the atmosphere. In such a distributed source scenario, the area affected by the carbon fiber dispersion could conceivably be larger than if all of the fibers were released in a single location.

6.4 FIRE PLUME RELEASE MODELS

This model describes the dispersion of carbon fibers released continuously and at uniform rate into a fire plume. The essential features of the model are shown schematically in Figure 6-1 (and also in Figure D-1). This figure is referred to in the description below of the various parts of the model. The equations indicated below have been coded into a computer program for ease of calculation.

The following assumptions were made in formulating the model:

CEILING OF MIXING DEPTH

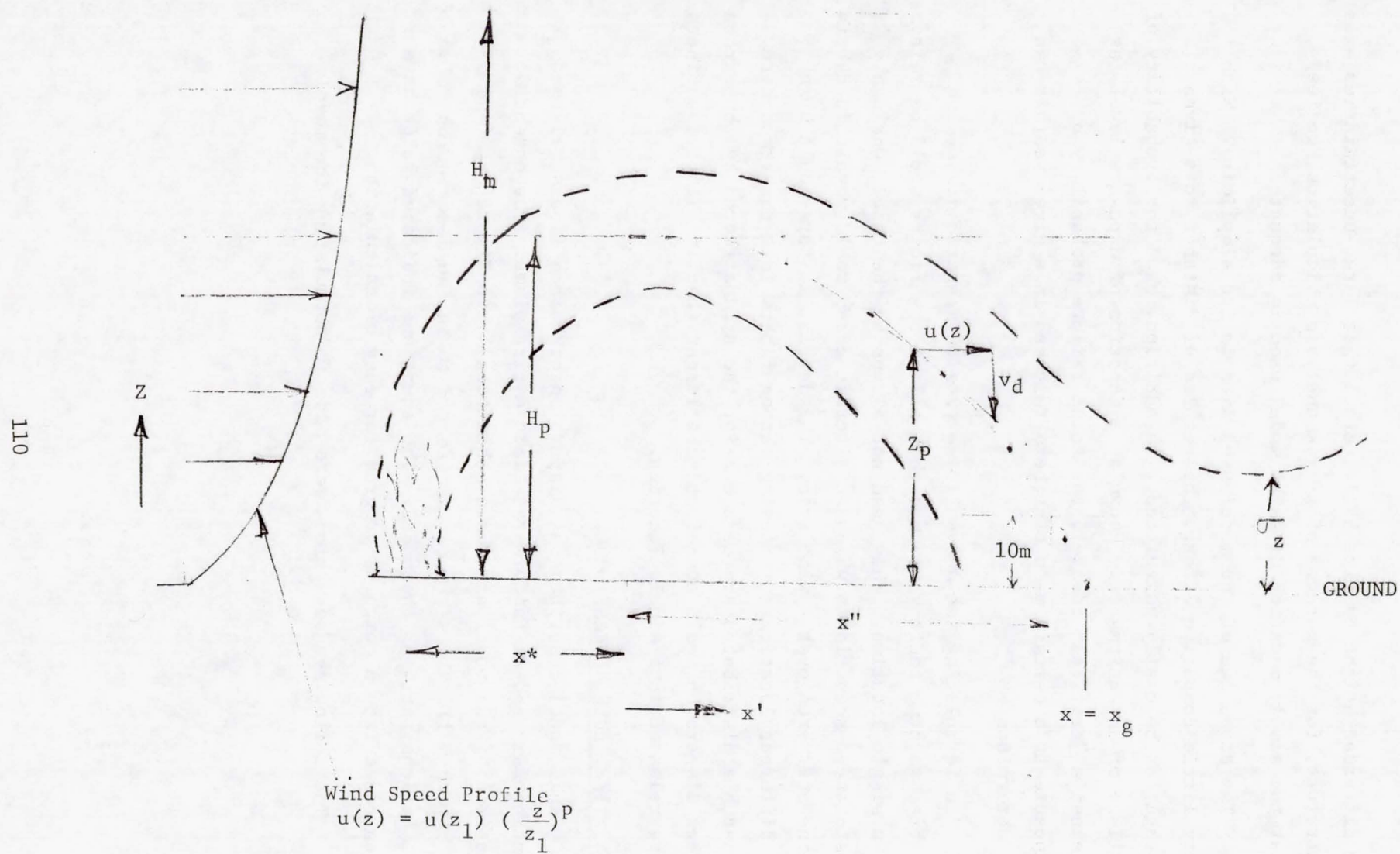


FIGURE 6-1: SCHEMATIC REPRESENTATION OF PLUME DISPERSION

Assumptions

1. Heat release rate from the fire is uniform (the principal burning component is JP-4 fuel).*
2. Fibers released are single fibers and all have the same terminal velocity.
3. Re-entrainment of the settled fibers into the dispersing cloud is negligible.
4. Fall-out of fibers from the thermal plume before it reaches the peak height is negligible.
5. Top of the mixing depth layer is above the maximum height to which plume rises.
6. Wind velocity variation with height is given by a power law.
7. Atmospheric stability category is the same throughout the region of dispersion of carbon fibers and remains the same over the duration of fiber dispersion

*Properties of JP-4

Heat of combustion	(Q)	=	43×10^6 J/kg
Heat of vaporization	(λ)	=	0.33×10^6 J/kg
Stoichiometric air-fuel mass ratio	(r)	=	14.8
Density of liquid	(ρ_L)	=	810 kg/m^3
Liquid regression rate	($\dot{y}$)	=	6.7×10^{-5} m/s.

Properties of air

Density of air (at 15°C)	=	(ρ_a)	=	1.2 kg/m^3
Specific heat of air	C_a	=		1004 J/kg K

Properties of large turbulent flame

Dilution ratio at the top of visible flame [That is the ratio of total air entrained within the fire to the stoichiometric air - Thomas et al (19)]	=	5
Fraction of total heat of combustion carried up in the convective plume after accounting for the heat lost by radiation from fire (η)	=	0.85
Ratio of diameter of plume at the top of fire to the fire base diameter.	=	1.3

Plume Calculations

The temperature rise of air in the plume above the ambient due to fire is:

$$\Delta T = \frac{Q \eta}{C_a (1 + 5\kappa)} \quad (6.9)$$

Density of hot gases at the top of burning zone is given by:

$$\rho = \frac{\rho_a T_a}{(T_a + \Delta T)} \quad (6.10)$$

Hence, the buoyancy parameter F is calculated by (see also equation 17 in Appendix D).

$$F = \frac{\dot{m}_f (1 + 5\kappa) g (1 - \rho/\rho_a)}{\pi \rho} \quad (6.11)$$

The plume rise height depends on the stability of the atmosphere. The height of rise is calculated using one of the following equations.

For Neutral and Unstable Atmospheres

$$H_p = 1.8 \frac{F^{1/3} \chi^{*2/3}}{\bar{u}} \quad (6.12)$$

Where

$$\chi^* = 67.3 F^{2/5} \quad \text{for } H_p > 300 \text{ m} \quad (6.13)$$

$$\chi^* = 2.164 F^{2/5} H_p^{3/5} \quad \text{for } H_p < 300 \text{ m} \quad (6.14)$$

For Stable Atmosphere

$$H_p = 2.9 \left(\frac{F}{\bar{u} s} \right)^{1/3} \quad \text{for } \bar{u} > 4 \text{ m/s} \quad (6.15)$$

$$H_p = 5 \left(\frac{F^2}{s^3} \right)^{1/8} \quad \text{for } \bar{u} < 2 \text{ m/s} \quad (6.16)$$

The mean wind speed $\bar{u}$ is calculated using the formula:

$$\bar{u} = u(z_1) \left[\frac{z_2^{(p+1)} - z_1^{(p+1)}}{(z_2 - z_1)(p+1) z_1^p} \right] \quad (6.17)$$

Generally, z_1 is taken as 10 m, because the normal wind speeds available from meteorological data refer to 10 m wind speeds. z_2 can be taken as the height (or depth) of mixing layer H_m .

The volume of p , which indicates the rate of variation of wind speed with height, depends on the stability of the atmosphere. Table 6-2 gives representative values. These are used in our model calculations.

Dispersion Formulae

The dispersion formulation is similar to that of Trethway [D.7]. Since the parameter of interest is the dosage of carbon fibers, the dispersion formulas are written to obtain the dosage. The general formula for fiber exposure at any location is written as

$$\text{Exposure} = (\text{Peak dosage}) \times (\text{y term}) \times (\text{z term}) \quad (6.18a)$$

i.e.,

$$D(x, y, z) = D_{\text{max}}(x) \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \times (\text{z term}) \quad (6.18b)$$

TABLE 6-2

Wind Speed Variation Index with Atmospheric
Stability Category

Atmospheric Stability Category	p	Remarks
Unstable (A through C)	0.1	$\frac{u(z)}{u(z_1)} = \left(\frac{z}{z_1} \right)^p$
Neutral (D)	0.13	
Stable (E, F)	0.16	

The z-term in the above equation accounts for the plume tilting due to settling of fibers and for the fact that fibers cannot penetrate either the inversion layer (top of the mixing layer) or the ground. The various terms in the above equation are evaluated as follows:

$$D_{max} = \frac{N(x)}{2\pi \sigma_y \sigma_z u(z_p)} \quad (6.19)$$

where $N(x)$ = Time integrated number of fibers contained in the plume and passing a section x .

$$u(z_p) = \text{wind speed at the height of the center of the plume.}$$

When the centerline of the tilted plume is far above the ground, the deposition of fibers on the ground is small. Therefore, in essence the plume can be considered as a "no mass loss" plume. However, once the centerline of the plume hits the ground surface,* the plume essentially spreads at ground level. Since the deposition rate is proportional to the fiber concentration in the plume and since the fiber concentration is now a maximum at ground level, the mass of fibers in the plume gets depleted.

This is taken into account by the equation:

$$N(x) = \begin{cases} N_0 & \text{for } x < x_g \\ N_0 p(x)/p(x_g) & \text{for } x > x_g \end{cases} \quad (6.20a)$$

$$(6.20b)$$

where N_0 is the total number of fibers released and $p(x)$ is the depletion function discussed in the previous section (see Equation 10 in Appendix D).

The term $u(z_p)$ in Equation 6.19 is the wind speed corresponding to the height of the plume centerline. However, when z_p is less than or equal to 10 m, the mean wind speed at 10 m level is used. Because of the wind speed variation with height, the plume tilt is not uniform. The following formula is used for evaluation of z_p :

* Deposition and hence mass loss starts being important when the height of the cloud centerline is about $2\sigma_z$ above ground. This has been ignored in our calculations.

$$z_p = H_p \left[1 - \frac{(p+1) V_d x'}{H_p u(H_p)} \right]^{(1/p+1)} \quad \text{for } z_p > 10m \quad (6.21a)$$

$$= \left[10 - V_d \frac{(x' - x'')}{u(10)} \right] \quad \text{for } 0 < z_p < 10m \quad (6.21b)$$

where x'' is that value of x' (see Figure 6-1) at which z_p is 10 m.
 x' is the downwind distance from the position where the height of the plume is a maximum.

The z -term in the exposure Equation (6.18) is given by:

$$\begin{aligned} z\text{-term} = & \exp \left[- \left\{ \frac{(z - z_p)^2}{2\sigma_z^2} \right\} \right] + \exp \left[- \left\{ \frac{(z + z_p)^2}{2\sigma_z^2} \right\} \right] \\ & + \exp \left[- \left\{ \frac{(z - z_p + 2H_m)^2}{2\sigma_z^2} \right\} \right] + \exp \left[- \left\{ \frac{(z + z_p - 2H_m)^2}{2\sigma_z^2} \right\} \right] \end{aligned} \quad (6.22)$$

The width at any position x downwind for a given fiber exposure level D^* on the ground is given by:

$$W(x) = 2\sigma_y \sqrt{2 \ln \left(\frac{D(x,y,0)}{D^*} \right)} \quad (6.23)$$

6.5 RESULTS FOR PLUME DISPERSION MODEL

The results from sample calculations for a fire plume release scenario are illustrated in Table 6-3. Results for the dispersion of 100 kg and 500 kg of fibers in neutral and stable atmospheres have been indicated for release in a 10-minute fire. It is seen that the principal effect of releasing the fibers into a plume is that the areas far down wind are liable to exposure. The near field areas may not be affected. For example, the release of 100 kg in atmosphere D in a fire plume causes the exposure level of 10^3 P s/m^3 at distances beyond 8 km (and up to 240 km!). As the stability of the atmosphere increases, there is increase in general both at the downwind distance at which the given ground level exposure levels starts, and the total area subjected to the exposure. This is due to the higher levels (in the atmosphere) to which the plume is lofted, the higher the atmospheric stability.

A comparison of the results for identical release quantities and weather types, but in the two different scenarios of dispersion (Tables 6-1 and 6-3), indicates some important features. Plume release may result in zero area for the given exposure level. However, when there is an area exposed to that level, the area is an order of magnitude larger than that which would result from a ground level release in the fire-explosion scenario. An example of this is the 500 kg release in D weather. For the exposure level 10^4 P s/m^3 , the total area covered in plume release is about $8 \times 10^8 \text{ m}^2$ whereas in the explosion release it is about $8 \times 10^7 \text{ m}^2$. Another principal difference is the downwind distance up to which the given exposure level exists. For the same example, for explosive release the maximum distance is 34 km whereas for plume release the distance (according to our model) reaches as far as 138 km.

For purposes of comparison with the results in Table 6-3, test calculations were made using the tilted plume method described in Pasquill as referred to above. The properties of the $10^3 \text{ particle-sec/m}^3$ isopleth were investigated for the conditions shown in the fourth line of Table 6-3 (i.e., $u = 2 \text{ m/sec}$, $v_g = 0.032 \text{ m/sec}$, $F = \text{stability}$, $H_p = 508 \text{ m}$). Concentrations were calculated assuming no reflection following the plume method

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VS: Deposition Velocity of Fibers (M/S) = 0.032

DOTMF: Fuel Burning Rate (KG/S) = 33.3

TIMEB: Total Time of Burning (S) = 600

DIAM: Diameter of the Pool (M) = 60

TA: Temperature of Atmosphere (K) = 288

TLAPSE: Temperature Lapse Rate in the Atmosphere = 0.03

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	1.0E6 FS/M ³				1.0E5 FS/M ³				1.0E4 FS/M ³				1.0E3 FS/M ³			
	NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA
IATM=4 U10=4 HM=1500 XSTAR=300 CFKGS=100 HP=403	0		0	0	0		0	0	0		0	0	8300		11048	6.86E8
		0		0		0		0		0		0		87300		
	WMAX occurs at X = 0				WMAX occurs at X = 0				WMAX occurs at X = 0				WMAX occurs at X = 75300			
IATM=4 U10=4 HM=1500 XSTAR=300 CFKGS=500 HP=403	0		0	0	0		0	0	10300		8080	4.63E8	6300		16107	1.11E9
		0		0		0		0		83300				94300		
	WMAX occurs at X = 0				WMAX occurs at X = 0				WMAX occurs at X = 74300				WMAX occurs at X = 77300			
IATM=6 U10=2 HM=1100 XSTAR=150 CFKGS=100 HP=508	0		0	0	50150		676	1.06E6	37150		5069	8.36E7	31150		7181	1.69E8
		0		0		52150				58150				61150		
	WMAX occurs at X = 0				WMAX occurs at X = 51150				WMAX occurs at X = 52150				WMAX occurs at X = 53150			
IATM=6 U10=2 HM=1100 XSTAR=150 CFKGS=500 HP=508	0		0	0	39150		4247	6.00E7	33150		6608	1.40E8	28150		8363	2.30E8
		0		0		57150				60150				63150		
	WMAX occurs at X = 0				WMAX occurs at X = 52150				WMAX occurs at X = 53150				WMAX occurs at X = 53150			

which is described by the profile "sinking" into the surface. Results from this technique are essentially the same as those reported in Table 6-3, well within the degree of approximation of both approaches. The X_{near} obtained is approximately 24,000 m and X_{far} , 72,000 m (compared with 28,150 m and 63,150 m respectively). W_{max} is approximately 7,400 m and occurs at 53,000 m (compared with 8,363 m and 53,150 m respectively). Finally, the area enclosed by the 10^3 particle sec/m isopleth is approximately $2.7 \times 10^8 \text{ m}^2$ compared with $2.3 \times 10^8 \text{ m}^2$ in Table 6-3. It can be concluded from this brief auxiliary investigation that, for the typical conditions chosen, the isopleth geometry is relatively insensitive to which of these mass loss models is applied to the plume.

The significance of these results, their accuracy and dependence on the assumptions made in the derivations of the models are discussed in the following section.

6.6 DISCUSSION

The dispersion models discussed above have incorporated most of the important physics of carbon fiber release and the dispersion. However, the models are far from complete and in many instances they may not represent the true situation accurately. The cardinal consideration in developing the above models was to make them detailed enough to account for all of the physical phenomena that take place, yet simple enough to use only those parameters that are easily available either from accident statistics or from routine meteorological data. For example, it is recognized that there exist horizontal wind shears in the upper levels of the atmosphere, the direction of the wind changing from layer to layer. The effect of such horizontal wind shears is to make the apparent dispersion in the horizontal direction much larger than is accounted for in the models described in the previous Sections. The magnitude of wind shear and its variation with height, atmospheric stability and location in the U.S. are not available. Therefore, while recognizing it to be an important phenomenon, it is not included in the models. The models used, however, give conservative (larger than actual) downwind penetration distances because of the suppression of lateral spread by wind shear.

The dispersion models used are basically Gaussian models which use the Pasquill dispersion parameters for the standard deviation of the Gaussian. It is noted that while Pasquill dispersion values can be applied with reasonable accuracy for dispersion within about 10 km. distance, their application to much larger distances is at best questionable. There is also disagreement between Pasquill and Cramer on the "law of variation" of vertical dispersion parameter (σ_z) with distance for all stability classes. Also, the effect of short duration release on the σ 's is not overly clear. This depends on the scale of eddies in the atmosphere. The scale varies with height as well as with atmospheric stability. However, because of the wide acceptance and usage of Pasquill curves for the σ 's (in atmospheric pollution studies) we have used these curves in our models.

There are other limitations with the dispersion models developed for use in carbon fiber dispersion analysis. For example in the plume model, it is assumed that no settling of fibers occurs between the fire and the location where the plume reaches its maximum height. The inherent error in such an assumption depends to a very large extent on the fiber size (settling velocity) and the stability of the weather. Heavy particles will possibly tend to fall out at relatively close distances from the fire, even though the hot gas plume may still be rising. An initial attempt has been made to quantify the precipitation of fibers during the ascending stage of the plume.* However, the analysis is not complete and is therefore not given in this report.

The dispersion models used are conservative in that the ground is modeled as a perfect reflector of particles for the evaluation of concentrations in air. This tends to make the effective residence time of particles in air longer, resulting in larger downwind dispersion distances and larger areas of coverage. A perfect "sink" approach to describe the ground absorption effect will underestimate the dispersion distances. A more appropriate description of the ground effect can probably be made only after the results from carbon fiber dispersion experiments become available. From a risk analysis point of view, conservative calculations, as indicated

* ADL internal memorandum

in this report, may suffice. The models also use the assumption that all of the fibers are released in the form of single fibers. This maximizes the hazard area for a given mass of fibers released.

The effects of changes in the terrain on the dispersion characteristics have not been considered. Because of the very large fiber travel distances (of the order of 100 km), it is highly likely that terrains do change. The change of terrain may have two principal effects. First, the ground characteristics may change resulting in different fiber retentivity. Second, and more importantly, the changes in ground characteristics and elevation may change the aero-dynamics of wind flow drastically so as to affect the dispersion of fibers very significantly. An example of this would be the presence of mountains, or very tall buildings. However, since the dispersion model developed is intended to be used for national risk assessment, individual site peculiarities (other than those that can be represented by the general climatological parameters) have to be ignored. Therefore, it is emphasized that the dispersion model used in this study is strictly applicable to reasonably flat grounds only.

Considerable judgement may have to be exercised in interpreting the results obtained from the models. The plume model, for example, predicts that dispersion distances for fiber exposure levels of interest is of the order of tens of kilometers. For release in low wind conditions (say 2 m/s wind speed) the duration of dispersion will be a significant part of the diurnal cycle of heating and cooling of ground. Under such long duration dispersion, the stability of the atmosphere would undergo appreciable change. The constant stability premise on which the models are developed is no longer valid. However, inclusion of such an hour-by-hour description of the state of the atmosphere in a risk analysis-oriented dispersion model will require considerable additional input, such as the time of day when accidents occur, the time of the year (which determines the heat flux from the sun and therefore the duration of a particular stability category) and perhaps the vertical variations in stability as well. Such detailed inputs are neither available nor necessary to perform a risk-type calculation.

One of the difficulties of using the dispersion results for evaluating the carbon-fiber-risk to electronic equipment is in the nature of the final result calculated by the models. The final result is in the form of ground areas subjected to a given exposure level (expressed in particle seconds per cubic meter). The exposure criterion does not contain the size of particles. For example, 10^5 P.S./m^3 can be formed by single fibers, or clumps of fibers acting in unison. The probability for damage to equipment will be (perhaps) different for the above two cases even though in toto the exposure level is the same. The dispersion models indicated cannot differentiate between the above two cases.

The models considered are not applicable to the case of dead calm. While one may visualize what may happen if the fibers are released in such a condition in a plume, (a fountain of fibers) no experimental data exist to quantify the dispersion. Hence it is not included in the models proposed. The effects of rain or snow were accounted for by a washout coefficient, but this was not implemented (see 5.4). The heat loss by radiation from the fire was accounted by a 15% factor. While this number is a variable and depends on fire size and soot concentration, for the purposes of present calculations, the above value is probably accurate.

The dispersion calculations are terminated at the point where the ground level exposure is equal to or less than 10^3 P.S./m^3 or where the downwind distance has exceeded 100km whichever is reached earlier; the amount of material remaining in the dispersing cloud at the location of termination of calculations is a relatively small fraction of the original released mass. Calculations of the product of ground contour area and the contour dosage (F.S./m^3) indicate that the product reaches a maximum at 10^4 F.S./m^3 exposure. The contours above 10^3 contain within them only 20 to 50% of the released mass of carbon fibers. The reason for this is quite simple. At very large distances downwind the standard deviations of the contours are also large. The center line fiber concentrations are low and the 10^3 P.S./m^3 exposure levels occur probably within the standard deviation. However, because of the Gaussian

distribution assumption, a substantial mass of fibers lies in parts of the Gaussian outside the 10^3 P.S./m³ contours. Since this mass of fibers is at very low concentrations (and hence low exposure values on the ground) the effect of the remaining mass of fibers on the overall risk analysis is minimal.

Finally, it should be noted that the principal difference in the treatment of the "reflection" boundary condition and the absorptive boundary condition lies in the description of the fiber concentration distribution above the ground. In both treatments however, there is removal of mass (of fibers) by settling or absorption. The values of the concentration of fibers at ground level with the two boundary conditions are quite different.

In the case of the perfect reflection condition the fiber concentration distribution above ground is that given by two sources of equal strength at equal distances (heights) on either side of the ground. Therefore the concentration profile has zero slope (with height) at the ground. The rate of mass depletion at ground level is proportional to the ground level concentration. The fibers settled do not further affect the concentration distribution. However, the mass of fibers in the dispersion cloud is reduced by the amount settled. This is precisely the perfect reflection particle settling model used by Slade [D. 12, page 204].

The tilted plume model of Pasquill [D. 5, p. 255] on the other hand assumes that the ground is like a sieve but that the full Gaussian (fiber concentration) profile sinks into it at the settling speed. Therefore the fiber concentration profile at the ground level does not have zero slope with height. The "sieve" in the ground acts like a perfect absorber; the mass of fiber above ground in the dispersing plume is given by that part of the Gaussian distribution above the ground level.

We have been consistent in the use of perfect reflection boundary condition for all three scenarios, i.e., explosive release, fire plume initial dispersion, and the tilted plume. The tilted plume model used by us is similar to that of Pasquill but differs in the treatment of the ground boundary condition. (See P. D-26 of the Appendix.) We have used the Slade perfect reflection condition.

7. BUILDING PENETRATION ANALYSIS

7.1 INTRODUCTION

The airborne exposure to carbon fibers experienced within a building may be substantially less than that outside the building. By their very nature, buildings provide a barrier to the free flow of airborne particulate contaminants through the air space they occupy.

The objective of this chapter is an evaluation of the degree to which buildings and other structures will attenuate potential exposures to carbon fibers. We aim at addressing most if not all types of buildings, and all phenomena which may influence the extent to which fibers in outdoor air can penetrate structures.

7.2 OVERVIEW OF BUILDING PENETRATION

Any given volume within a building is potentially surrounded by numerous "sources" through which contaminants in outdoor air may enter, and, "sinks" through which they will eventually leave or become entrapped. Among the potential sources are included 1.) constantly open doors and windows; 2.) air leakage through openings around or through normally closed windows, doors, walls, ceilings, louvered areas, and air vents; and 3.) ventilation systems which force fresh air into the structure. Sinks include 1.) air filters in building ventilation systems; 2.) other ventilation system components which capture dust and/or provide a surface upon which it may settle; 3.) exposed room surface areas upon which dust may settle; and 4.) building materials and crack spacings which tend to capture solid contaminants being conveyed by infiltrating air volumes. In the following, we briefly describe each of these topics.

Open windows or doors to the outside are the most obvious inlet sources, and are those which can easily dominate any analysis involving building penetration. For an example, consider a room with dimensions of 40 x 10 x 10 feet. If the room has a normal size window at each end, and each window is open to a height of only 6 inches, every

mile per hour of external wind velocity may cause displacement of an entire room volume of air approximately every hour. At wind speeds of even a few mph, one can visualize how rapidly contaminants in outdoor air would pervade this room.

With very few exceptions, air leaks into virtually any type of structure constructed of ordinary building materials. In Appendix E.2 we show that the extent of such leakage, called "infiltration," can typically range from 0.2 to 1.5 complete air changes per hour (ACPH) in residences, and from 0.2 to 1.0 ACPH in office buildings. For the hypothetical room we considered above, therefore, infiltration effects can be equivalent to about a one mph "wind" of outdoor air.

Finally, we must consider ventilation systems which mechanically force outdoor air volumes into buildings in order to replenish oxygen supplies, and dilute odors and cigarette smoke. It is not uncommon for such systems to replace an entire building's air volume every 4 to 15 minutes.

The first sink we specifically consider for carbon fibers involves air filters which may be utilized in a building's ventilation system. Such filters are available in many different forms, and are commonly if not universally used. By capturing a fraction of the dust which is normally found in the outdoor atmosphere, they help keep components of the ventilation system (fans and coils, e.g.) from becoming clogged with dust, and simultaneously serve to reduce dust levels in internal occupied spaces. High quality filters can essentially capture all carbon fibers attempting to penetrate a building, and can thus negate the potential for the ventilation system to act as a "source" of carbon fibers. Lower quality filters, however, can only reduce, but not eliminate, the extent to which fibers may enter this route.

Besides air filters, typical building ventilation systems may be comprised of fans, heating or cooling coils, and lengths of circular or rectangular ducts. If carbon fibers should pass through air filters, there is potential for some fraction to settle upon the exposed surfaces of these components and to remain imbedded there in layers of common dust

and soot particles.

Our third sink involves the exposed surfaces in the occupied spaces of a building. Since carbon fibers are considerably heavier than air, they will tend to settle out of the air onto such surfaces. This action essentially removes them from consideration as airborne contaminants in the space.

Finally, we consider a sink which is more difficult to visualize, and which involves the ability of typical construction materials to capture aerosols in air volumes infiltrating a building. Infiltration is partly the leakage of air into a building through the small cracks and crevices around the individual components used to construct a building. Although molecules of air can pass through many of these openings unimpeded, relatively large carbon fibers will not always be as successful.

7.3 MODEL DEVELOPMENT

7.3.1 Introduction

To facilitate evaluation of the wide variety of occupancies of interest to this analysis, we developed an analytical model representing the interactions between potential sources and sinks of carbon fibers. The model is sufficiently detailed to account for the majority of phenomena of concern, yet simple enough to ensure the manageability of data collection efforts.

Directly below, we present the equations which comprise the basic model as utilized in the building penetration analysis. This discussion is then followed by one detailing various simplifying assumptions.

7.3.2 Model Equations

As the leading edge of a cloud of carbon fibers infringes upon the outer boundary of a building, and the cloud begins to envelop the structure, one can expect that the indoor concentration of carbon fibers will begin to increase (if there is any feasible entrance route of fibers). If the external exposure is of sufficient time duration, the

internal concentration may level off at some steady-state value. Otherwise, it may still be on the increase when the tail edge of the cloud passes the building.

At the instant the tail edge of the cloud has passed, internal areas will still contain airborne concentrations of carbon fibers. As fibers continue to settle out of the air onto exposed surfaces, and as entering air volumes dilute remaining concentrations with now clean outdoor air, internal areas will rapidly be purged of airborne fibers.

To model these phenomena, it is necessary to address the concentration build-up phase separately from the purging phase. In both cases, it is desired to develop concentration as a function of time relationships which can then be integrated over appropriate time durations.

Figure 7-1 displays a diagram of an internal space within a building and presents the equations which comprise the building penetration model. A detailed derivation of these is provided in Appendix E.3 while section 7.3.3 below discusses the various assumptions utilized in the analysis. It should be noted that there is a slight variance between the first two equations presented on the figure and those which are derived in the appendix. This variance simply stems from a redefinition of units for airflow volume rates, and does not affect proper applications of these expressions. Nomenclature utilized is defined in Table 7-1.

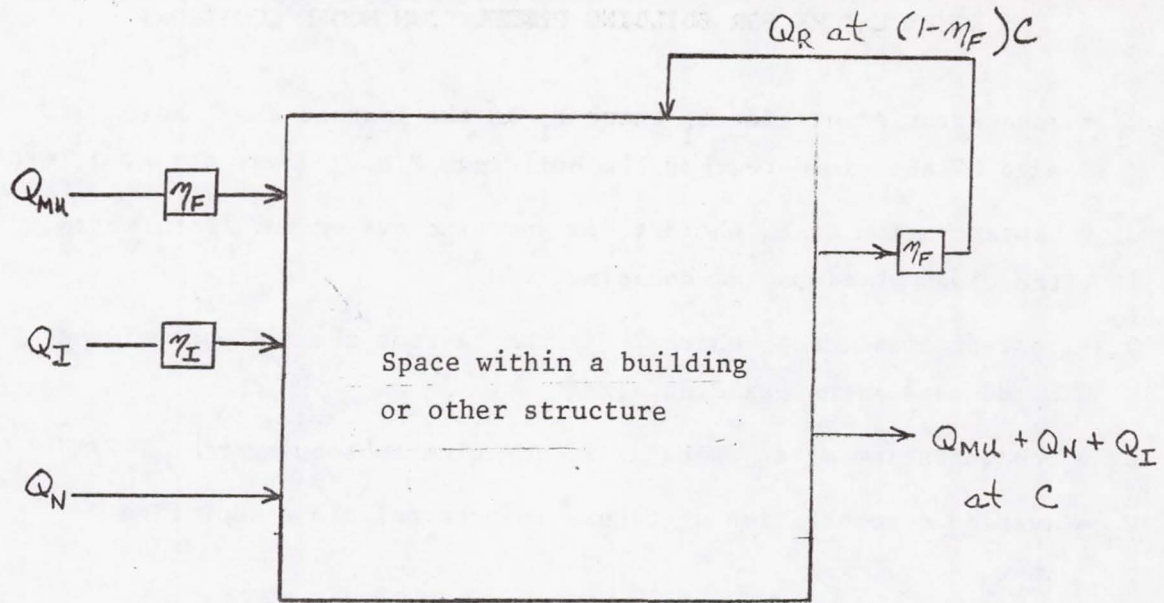
The expression of most significance is that which defines the value for the internal airborne exposure transfer function (AETF) value. As simple inspection of Figure 7-1 will show, multiplication of this function value by the exposure external to building boundaries directly provides a predicted internal exposure.

7.3.3 Major Assumptions for Model

Perfect Mixing

All significant entrance routes of carbon fibers into internal building areas entail the movement of contaminated air volumes. These

FIGURE 7-1
BUILDING PENETRATION MODEL



During concentration build-up:

$$C_2 = \frac{\bar{C}_0 [(1-\eta_F)Q_{MU} + Q_N + (1-\eta_I)Q_I]}{Q_{MU} + Q_N + Q_I + \eta_F Q_R + \frac{V_S}{H}} \times \left[1 - \exp \left(- \left(Q_{MU} + Q_N + Q_I + \eta_F Q_R + \frac{V_S}{H} \right) (t_2 - t_1) \right) \right]$$

During purging process:

$$C_3 = C_2' \exp \left[- \left(Q_{MU} + Q_N + Q_I + \eta_F Q_R + \frac{V_S}{H} \right) (t_3 - t_2') \right]$$

For integrated internal exposure:

$$E = \left[\frac{Q_N + (1-\eta_F)Q_{MU} + (1-\eta_I)Q_I}{Q_N + Q_{MU} + \eta_F Q_R + Q_I + \frac{V_S}{H}} \right] \bar{C}_0 (t_2' - t_1)$$

Definition of internal airborne exposure transfer function (AETF):

$$AETF = \left[\frac{Q_N + (1-\eta_F)Q_{MU} + (1-\eta_I)Q_I}{Q_N + Q_{MU} + \eta_F Q_R + Q_I + \frac{V_S}{H}} \right]$$

TABLE 7-1

NOMENCLATURE FOR BUILDING PENETRATION MODEL EQUATIONS

- C_1 = concentration at time t_1 where t_1 is the instant the leading edge of the cloud reaches the building, F/M^3 (fibers per cubic meter)
- C_2 = concentration at t_2 where t_2 is any time subsequent to t_1 while the cloud envelops the building, F/M^3
- C_2' = concentration at t_2' where t_2' is the instant the tail-end of the cloud passes the building, F/M^3
- C_3 = concentration at t_3 where t_3 is any time subsequent to t_2' , F/M^3
- $\bar{C}_o$ = average concentration of fibers in external cloud (duration is $t_2' - t_1$), F/M^3
- E = internal exposure to airborne carbon fibers, FS/M^3 (fiber-second/ m^3)
- H = ceiling height of affected space, M
- Q_{MU} = mechanically provided fresh air inlet rate, air changes per hour (ACPH)
- Q_R = air recirculation rate, ACPH
- Q_N = natural ventilation rate, ACPH
- Q_I = infiltration rate, ACPH
- V_S = settling velocity of fibers in still air, M/S
- η_F = overall efficiency of installed air filter banks for capturing carbon fibers, non-dimensional fraction*
- η_I = crack capture efficiency, i.e., efficiency of building materials and crack spacings in capturing fibers in infiltrating air volumes, non-dimensional fraction*

*An efficiency of 0.90 indicates that 90 percent of fibers will be captured.

volumes will vary in rate of entrance and specific contamination level. Additionally, they will enter any specific internal space from different boundary locations.

Our first simplifying assumption is commonly utilized, and involves the assumption that all air volumes entering a specific internal space will instantly and perfectly mix with all air volumes which occupy that space. It allows us to ignore details of the complex interactions between air streams of differing strength and orientation, and forces attention upon the overall average contamination level expected.

Earlier literature dealing with the dilution of airborne contaminants within an industrial setting typically suggests that actual contaminant levels at specific sites may be greater than the overall average by a factor in the range of 3 to 10. However, more recent work has shown that the "mixing factor" is more often on the order of 2, and sometimes considerably less than 1. This latter finding is completely logical since it recognizes the law of mass conservation and its application to the scenarios of interest.

In consequence, our assumption of perfect mixing has the following ramifications:

- It ignores the possible adverse effects of "hotspots" within a given space; and
- It ignores the possible benefits to the analysis of spots which are less contaminated than average conditions.

Single Compartments

A ventilation system will often be intended to provide a specific rate of ventilation to all spaces within a building. Unless it is perfectly designed, however, it is likely to provide rates to specific rooms which are somewhat greater or less than desired.

Open windows in one area of a building may tend to result in greater contamination of that area relative to other areas. This will be especially true when the other areas are distant and not directly influenced by contaminants entering open windows or doors.

Finally, one can understand that infiltration involves air leakage into a building from a variety of entrance locations. It is not necessarily a uniform effect, and may be concentrated near building entrances and exits, elevator shafts with open air vents, and peripheral building areas with many windows.

Variations such as these are difficult to address even when one is dealing with a specific building under a specific and known set of operating and environmental conditions. When considering the universe of all types of structures, and all feasible conditions, it becomes impossible to fully treat the resulting interactions. In consequence, our third assumption is that we can reasonably consider building areas with similar purposes as one large open area instead of a number of smaller areas with differing characteristics.

By stating this assumption, we are essentially extrapolating our previous perfect mixing assumption from the boundaries of any specific room to the outer boundaries of all building spaces with similar purposes. Thus, the advantages and disadvantages of this action are analogous to those discussed above for perfect mixing.

Deposition in Ventilation System Components

As formulated, the model does not address the possibility of carbon fiber deposition upon the exposed surfaces of ventilation system components such as fans, heating or cooling coils, or ductwork. In this respect, the model may be decidedly conservative in a few feasible scenarios.

The scenarios in which we envision the model may be conservative involve:

- Normally closed windows and doors (i.e., negligible natural ventilation); and
- Poor quality and/or poorly fitted air filters in a forced air ventilation system; and
- Minimal entrance of carbon fibers within infiltrating air volumes; and
- Significant duct lengths or "density" of ventilation system components within the ductwork.

If the natural ventilation rate is high relative to other air volume rates, as is quite easily achievable with a few open windows and even a relatively low external wind velocity, the contaminant inlet rate through this route will dominate any building penetration analysis. Thus, depositions in ductwork would be an insignificant factor in most scenarios involving open windows, doors or louvers to the outside.

We will show in Appendix E.2 that medium to high efficiency air filters can capture virtually all fibers entering through a ventilation system when the filters are properly installed. Obviously, if the filters stop fibers from entering, the possible attenuation provided by deposition in ductwork becomes an irrelevant factor. In order for such deposition to be important, either the filters must be of low quality, or they must be poorly fitted into holding frames such that a significant amount of fibers pass through the filters.

When a building area can be characterized as having numerous sources of infiltration, and these sources can successfully allow carbon fibers to enter, the contaminant entrance rate through this route can also dominate an analysis. Thus, the building area of interest must be relatively immune to contamination by this route for duct deposition to be important.

Finally, we must realize that the distance from an outdoor air intake to any specific room can vary widely, and that the "density" of components within the ductwork can vary depending upon the specific purpose and design of the ventilation system. In order for deposition to be significant, either duct lengths must be long or the internal components must have a propensity for capturing dust which passes through air filter banks.

In summary, we find that duct deposition effects might be most significant in buildings which are tight (modern office type construction, no elevators, sealed windows, low traffic through doors, etc.), which utilize low efficiency filters and/or poorly maintained filter banks, and which have full heating, ventilating, and air conditioning (HVAC) systems with considerable duct lengths. In the majority of other scenarios, such deposition may not be significant.

With this limited but common scenario in mind, we gave thought to how we might incorporate duct deposition effects into a model which could be generally applied and to what the results of this effort would be. This led to the determination that we would have to assume duct deposition is negligible at one extreme (when duct lengths to specific rooms are short and/or air velocities are high), and very significant at the other (when lengths are long and/or air velocities are low).

Since it had become evident that we would essentially be generating a range of airborne exposure transfer function (AETF) values for each type of occupancy, we would not affect the upper bound of the range when assuming negligible deposition. We would, however, be lessening in magnitude the lower bound of predicted AETF ranges when deposition was considered significant.

Preliminary computations showed that lower bounds for AETF ranges were such that it would require extreme and unusual external building exposures to carbon fibers to adversely affect electrically energized equipment within the building. In direct consequence, we concluded that little would be gained by complicating the model and data collection efforts by incorporating possible duct deposition effects within the overall analysis procedure.

Airflow Balance

It is assumed that the total volume rate of air entering an internal space of interest is exactly equal to the rate of air leaving.

Fiber Conservation

Carbon fibers are rather brittle, and have a tendency to break into two or more pieces when subjected to sufficient stresses. Our

basic approach to model development assumes that airborne concentrations or exposures will not increase due to this possibility as fibers enter an internal space. Rather, we have accounted for this eventuality in a very limited fashion in the process of defining air filter efficiencies for carbon fibers.

Re-entrainment

The model assumes that any fiber which settles on an exposed horizontal surface in a room will permanently stick to that surface, or at least, will not move in a fashion which contributes to the magnitude of airborne exposures therein.

Settling Rate

The free fall velocity of carbon fibers in still air is a function of specific size, shape, and density characteristics. These will vary from one specific product to another.

For the portion of this risk analysis dealing with external dispersion phenomena, it was assumed that an appropriate average settling rate for use is 3.2 cm per second (378 ft per hour). Similarly, it is assumed here that this value is of adequate validity for general use.

Late Passage Through Filters

Limited experimentation has been conducted concerning the efficiency of common air filters to capture carbon fibers. In a specific study of minimal quality filters, it was noted that individual fibers may pass through filters at times long after fibers were no longer being introduced to the air stream. As formulated, the model does not account for these delayed reactions, and essentially assumes that this phenomenon would be peculiar only to filters of the lowest quality.

Equipment Cabinets

The basic objective of this penetration analysis was to estimate the exposures to carbon fibers expected in the immediate vicinity of electrically energized equipment. The analysis does not give credit for the possible protection afforded by equipment cabinets and air filters within such casings. Rather, it is assumed that such factors have been taken into account in the process of assigning mean exposure to failure levels for the various classes of equipment.

7.4 DATA COLLECTION EFFORTS AND RESULTS

7.4.1 Introduction

The model requires values for seven parameters before it can be applied for any given type of occupancy. Appendix F describes in detail our efforts relating to data collection and presents the rationale behind the selection of specific parameter values for use in the model. In the following, we generally discuss the nature of our findings and describe some basic assumptions.

7.4.2 Realworld Variability

The most striking result of visits to numerous facilities was the finding that there is sometimes great variability between pertinent characteristics of internal spaces, even when these spaces are devoted to similar functions. For example, in buildings housing the transmitters of five radio stations, we found widely divergent conditions.

One transmitter and its associated equipment were in a large room with essentially sealed windows and no mechanically provided fresh air supply. Thermostatically controlled packaged air-conditioning units could only recirculate air. A room such as this could only be contaminated by carbon fibers if the fibers entered with infiltrating air volumes, yet this must be considered a low probability event given the obvious "tightness" of the area, and the fact that the room is infrequently manned.

A second set of equipment in a basement room of the same building continually exhausted cooling air to the outdoors with no provision for recirculation. The only filter used in the room served one-half the actual transmitter cabinet and nothing else. Make-up air entered the room from a corridor through square holes in a wall. Under a variety of operating conditions, this air had the potential to be contaminated with carbon fibers, since there were many possible sources of unfiltered air nearby.

Next door, in a similar room, was the transmitter for a third station. Here, someone had taken great care to ensure minimal dust contamination. The metal door had been recently weather-stripped, and the transmitter cabinets and the area through which make-up air entered had been specially fitted with good quality air filters. Additionally, it was evident that all air could be recirculated in cold weather to conserve heat.

At another site, the ventilation system serving transmitter cabinets and a control room was obviously a patchwork affair with a somewhat unstable temperature control system. It was patently obvious that large volumes of completely unfiltered air could enter the control room (no air filters were used). The situation for the transmitters was somewhat better, but still far from ideal.

Finally, we learned of a new building being built near a seashore. To protect their new high-power transmitters, station personnel had decided to provide virtually clean room conditions.

To account for these major differences, we found it necessary to specify ranges of values for each parameter, and to compute a range of AETF values which encompassed the best and worst conditions we could envision. Although these ranges sometimes span a number of orders of magnitude, we are confident they provide an honest appraisal of the situation in the real world.

7.4.3 Guidebooks, Standards, and Codes

The literature abounds with recommendations concerning ventilation rates, minimum filter efficiencies, recirculation rates, etc. for different types of occupancies. Nevertheless, we often found that building architects and/or tenants ignored such recommendations.

In consequence, regardless of their source, we utilized literature recommendations only as guideposts in selecting parameter values, with the assumption that at least some fraction of buildings must have been designed with these recommendations in mind.

Where equipment manufacturers had specified air quality requirements for rooms housing their equipment (computer manufacturers, e.g.), or where there were Federal standards governing such matters (for certain hospital areas), there was more consistency in our observations. Nevertheless, variations were evident.

7.4.4 Regional Differences

Our site visits were to four specific geographical areas, as described in Appendix B. Although limited in scope, they did not result in the identification of unexpected and significant regional differences

in the building penetration aspects of our problem. Pending further investigation, we therefore concluded that so much variability can be found in any one region that our computed ranges for AETF values are valid for nationwide use.

Expected variations were at least qualitatively observed, if not fully reported upon. Obviously, the different climatic conditions in differing locales, the age of a city and its wealth, and other factors determined the extent to which one might find open windows or doors in buildings and/or might find a greater fraction of older factory type buildings versus more modern facilities.

7.4.5 Distribution Data Needs

From an overall perspective, we found we were able to estimate ranges of AETF values applicable to numerous categories of occupancies. These ranges were sometimes wide because of extreme variations in observations, and/or because of seasonal differences in natural and mechanical ventilation practice.

Our site visits indicated that some fraction of the occupancies of concern would more typically be represented by the high end of a range, or conversely, by the low end during any particular season. Additionally, they indicated that these distributions could vary with climatic conditions. Herein lay the root of a somewhat unexpected problem.

Although our field work had identified examples of structures resistant to penetration, and structures not so resistant, it had not involved sufficient numbers of buildings for us to define what fraction of structures are represented by each point within any specific AETF range. In consequence, we were forced to assume such distributions based upon judgment, as listed in Table G-4.

Further refinement of our methodology for the building penetration model, would require investigation of a larger sample size of each occupancy type of interest. This would allow us at some point in the future to better estimate the necessary distributions.

7.5 SUMMARY OF RESULTS

Table 7-2 summarizes the overall results of the building penetration analysis. As will be noted, we have considered one or more sets of conditions for each area designation addressed, and we have utilized the model to compute a representative range of AETF values.

The upper limits of these AETF ranges were computed by using the set of model parameter values which provided the highest AETF value. These limits, therefore, represent the worst case situations expected in some fraction of each area designation of concern under specified scenario conditions. Conversely, the lower limits represent the best case situations we would expect to find in studying any particular category of occupancies.

7.6 UNCERTAINTIES AND THEIR INFLUENCE ON RESULTS

Uncertainties introduced by the assumptions utilized to develop the building penetration model can be deduced from the preceding text. We are of the opinion that the equations presented are sufficient to predict internal exposures within an order of magnitude (or less) in the vast majority of cases when they are provided with exact input data.

In general, our assigned ranges of mechanically provided, natural, and infiltrating ventilation rates are considered sufficiently accurate for input to the model, as are the rates of recirculating air volumes. Although minor refinements may be possible, we do not foresee the finding of significant inaccuracies in these data. The situation is similar for the ceiling heights and the carbon fiber settling velocity used in computations. Significant variations would be necessary to modify any upper or lower bound of AETF ranges by more than a factor of 2 or 3.

Somewhat greater uncertainty is associated with our assessment of the efficiency of commonly used air filters to capture carbon fibers, and with the manner in which we used these data. However, since the efficiency ranges estimated for any particular grade of filter generally vary from a very conservative value to a non-conservative value, our uncertainty only served to widen AETF value ranges.

Similar uncertainties relate to the variation we observed in the types of filters utilized at similar facilities. In cases where we actually observed a wide range of filter efficiencies, we were certain that there were considerable variations from building to building. However, when we only visited one or two examples of a facility type, and found similar filters being utilized, the situation became less clear. We simply were not certain whether all such facilities use such filters, or whether our small sample size was misleading us. In consequence, we must point out the possibility of significant exceptions to our findings for certain categories for which we made blanket statements regarding filtration practice.

The greatest degree of uncertainty is associated with the selection of values for η_I , the crack capture efficiency. However, our choice of range limits is likely to have encompassed both best and worst case conditions.

Overall, we generally conclude that the ranges of AETF values encompass expected real world conditions. Although there is some potential for a specific upper or lower bound to be in error by more than an order of magnitude, we consider this to have low probability. Not only would a range bound for some specific parameter have to be considerably in error, but all other parameters would simultaneously have to reflect either best or worst case conditions.

TABLE 7-2

AETF SUMMARY OF RESULTS

<u>Area Designation</u>	<u>Scenario Conditions</u>	<u>AETF Range</u>
Aircraft Cabins and Cockpits	All doors closed, HVAC system off.	$0.0 \text{ to } 9.2 \times 10^{-4}$
	Cabin and cockpit doors open, HVAC system on or off.	0.16 to 0.68
	Doors closed, HVAC system on, 727 or 737 craft only.	$1.0 \times 10^{-4} \text{ to } 8.2 \times 10^{-2}$
	As above, all other commercial airliners.	$1.0 \times 10^{-4} \text{ to } 0.135$
Aircraft External Compartments	Nose section radome.	$1.3 \times 10^{-3} \text{ to } 9.5 \times 10^{-2}$
	Wing flap compartments.	$7.6 \times 10^{-3} \text{ to } 2.7 \times 10^{-2}$
	Wheel well areas.	$\sim 2.2 \times 10^{-3}$
Airport Baggage Make-Up Areas	Garage doors constantly open.	0.32 to 0.87
	Doors sporadically open.	$7.4 \times 10^{-2} \text{ to } 0.14$
Airport Control Tower Buildings	Open windows.	$1.3 \times 10^{-2} \text{ to } 0.5$
	Closed windows.	$0.0 \text{ to } 6.5 \times 10^{-3}$
Airport Passenger Terminals	Generally closed windows and doors.	$0.0 \text{ to } 1.0 \times 10^{-2}$
Airport Radar Transmitter Buildings	Normal operating condition.	$0.0 \text{ to } 1.1 \times 10^{-2}$
Airport Runway Buildings (Misc.)	Windows or doors open.	$1.9 \times 10^{-2} \text{ to } 0.61$
	Closed buildings with window air-conditioners (AC) operating.	$0.0 \text{ to } 1.1 \times 10^{-2}$
	As above with AC or other HVAC system off.	$0.0 \text{ to } 5.8 \times 10^{-3}$
	Closed buildings with operational exhaust fans.	$7.7 \times 10^{-3} \text{ to } 4.2 \times 10^{-2}$
Banks	See "Office Areas" with medium efficiency air filters for general areas.	
Computer Rooms	All cases.	$0.0 \text{ to } 3.0 \times 10^{-3}$

<u>Area Designated</u>	<u>Scenario Conditions</u>	<u>AETF Range</u>
Department Stores	See "Retail Outlets"	
Elevators	Machinery and control rooms as well as door operator motor areas.	6.6×10^{-2} to 0.50
Emergency Power Generators	Outdoors in housings or buildings without air filters.	~ 1.0
	As above, with air filters.	1.0×10^{-2} to 0.70
	Indoors within maintenance areas with non-filtered air supplies.	0.24 to 0.66
	Indoors within maintenance areas with HVAC systems and filters.	2.4×10^{-3} to 0.16
Health Facility General Areas*	Open windows or external doors.	1.5×10^{-2} to 0.44
	Closed windows and doors.	0.0 to 6.5×10^{-3}
Health Facility Laboratories	Closed windows or external doors.	0.0 to 1.0×10^{-2}
	Open windows and doors.	1.3×10^{-2} to 0.43
Health Facility Operating Rooms	Normal status.	0.0 to 3.5×10^{-4}
Health Facility Patient Rooms and Corridors	Closed windows and external doors.	0.0 to 6.6×10^{-3}
	Open windows or doors.	1.5×10^{-2} to 0.44
Health Facility X-Ray Areas	Normal status.	0.0 to 3.3×10^{-3}
Industrial Buildings	Older factory type building with closed windows, no forced air system.	3.9×10^{-3} to 0.2
	As above, but with many open doors and windows.	0.3 to 0.7
	A tight modern building with closed windows and no forced air system.	0.0 to 6.4×10^{-3}
	As above, but with mechanically provided non-filtered air supplies.	1.5×10^{-3} to 0.48

* Includes recovery rooms, intensive care areas, isolation rooms, examination rooms, treatment rooms, physical therapy and hydrotherapy areas, sterilizer equipment rooms, and food preparation centers.

<u>Area Designated</u>	<u>Scenario Conditions</u>	<u>AETF Range</u>
Office Areas	As directly above, using low efficiency air filters.	7.6×10^{-5} to 0.13
	As above, using medium to higher efficiency air filters.	0.0 to 3.3×10^{-2}
	As above, using high efficiency filters for clean or semi-clean room conditions: 0.0 only.	0.0
	Any scenario with open windows.	1.2×10^{-2} to 0.63
	Closed windows and low efficiency filters	4.3×10^{-4} to 7.0×10^{-2}
	Closed windows and med/hi efficiency filters.	0.0 to 5.9×10^{-3}
	Closed windows and HVAC system off.	0.0 to 6.4×10^{-3}
	Closed windows and working unit ventilators with low efficiency filters.	0.0 to 1.5×10^{-2}
	Radio Station Studio and Control Areas	Normal status.
	Radio Station Transmitter Sites	For control rooms and transmitter areas under normal conditions.
Residences	Open windows or doors.	1.1×10^{-2} to 0.70
	Closed windows and doors.	0.0 to 9.6×10^{-3}
Retail Outlets	Internal store areas.	9.4×10^{-5} to 9.0×10^{-2}
	Cash register areas near busy exits and entrances.	5.2×10^{-3} to 0.12
Telephone Company Equipment Installations	Normal status.	0.0 to 9.2×10^{-3}
TV Station Studio Buildings	General areas.	0.0 to 4.1×10^{-2}
	On-camera studios.	0.0 to 0.10

<u>Area Designated</u>	<u>Scenario Conditions</u>	<u>AETF Range</u>
TV Station Transmitter Sites	Control room with open windows and HVAC system off.	3.2×10^{-2} to 0.16
	Control room with closed windows and HVAC system off.	0.0 to 1.0×10^{-2}
	Control room with closed windows and HVAC system on.	0.0 to 6.2×10^{-2}
	Transmitter housings.	0.0 to 2.3×10^{-2}
Utility Supply Areas	Closed room without ventilaion.	1.3×10^{-3} to 2.3×10^{-2}
	Open windows, doors, or louvers, with or without mechanical ventilation.	9.6×10^{-2} to 0.50
	Closed room with filtered air supply.	1.7×10^{-3} to 9.7×10^{-2}

8. EQUIPMENT VULNERABILITY ANALYSIS

8.1 INTRODUCTION

Carbon fibers are conductive, and when they come into contact with circuitry, they are capable of disabling or destroying that circuitry by allowing undesirable paths of electrical flow between individual components. The resulting effects can range from a brief and partial circuit interruption to the destruction of components due to arcing or fiber burn-out. Besides circuitry, other types of electrically energized equipment are also susceptible to adverse effects.

The potential vulnerability of a specific type of equipment to carbon fibers is a function of many complex factors, including but not limited to the size, shape and electrical characteristics of the carbon fibers, the electrical characteristics of equipment components, and the airborne dosage to which the equipment is subjected.

It is the intent of this chapter to briefly describe what is known on the topic, and to present our approach in assessing the specific vulnerabilities of equipment types of interest. We do not provide detailed discussions, or specific examples, because much of the source material is classified and therefore unavailable to the general public.

8.2 ELECTRICAL CHARACTERISTICS OF CARBON FIBERS

The resistance of carbon fibers can range from a few hundred ohms/cm to several thousand ohms/cm. Individual fibers bridging a pair of electrical contacts can cause a short or low leakage paths, which may result in equipment failure. For low energy circuits such as normally found in many semiconductor applications, the lowered resistance path can cause complete or at least partial circuit interruption. Basic characteristics of typical fiber materials are listed below:

FIBER	RESISTANCE (ohn/cm)	BURN OUT PARAMETERS		
		Potential (Volts/cm)	Current (mn)	Power (w/cm)
GY-20	1070	14.3	23.9	0.342
HMS	2000	22.3	13.1	0.292
TH-75	3160	22.6	12.3	0.277
F-40	472	14.8	33	0.49
F 41	140	10.4	78.5	0.82

The disabling resistance levels for a range of component types or circuit applications have been reported in the literature.[1]

The disabling resistance characteristics of electronic equipment are the root cause of equipment failures when they are subjected to an exposure to carbon fibers. The concentration of fibers and the duration of exposure required to cause failure are the subject of several hundred tests. In Section 8.8, these data have been examined and analyzed to determine trends or critical levels.

A single fiber across two conducting paths of a printed circuit board or bridging two contacts of a connector or the leads of an integrated circuit could disable the circuit function. The electronic equipment in use in the facilities under study could be seriously damaged by such a failure. On the other hand, it is possible to apply a heavy coating of particles on a board, and by chance no shorts or low impedance paths would be developed and no damage would result. This latter circumstance is particularly true if a printed circuit card had been protected by a conformal coating. This condition is quite common in those equipments designed for adverse environmental conditions.

Similarly, a cloud of conductive material in the direct vicinity of high-voltage circuitry could initiate a breakdown that could either disable the high-voltage circuitry or cause transients that might adversely affect adjacent digital data handling. Another effect might be only a high-voltage burn-out or clearing of the contaminant with no detrimental affect. The scenarios are so complex and unpredictable that for this evaluation we must rely upon the results of field data that have been reported to us.

8.3 POSSIBLE EFFECTS ON EQUIPMENT OF DIFFERENT PARTICLE SIZES

The early recorded data on vulnerability is largely oriented toward effects of fibers of the order of 1 to 10mm in length, [2] Actual exposure from an accidental release may result in any combination of three general classes of fibers, and these classifications were considered in the extrapolation of recorded test results to possible real-life scenarios.

The first general class consists of large clumps or masses of fibers several inches in length. Because of their mass it is not expected that this class of particles will be airborne for any great distance. Potential damage would be limited to the near vicinity of the release. The large size of the particles would probably preclude their entry into enclosed electronic equipment, as well as into buildings or other enclosures housing electronic equipment. However, if any of these particles rested on rotating machinery such as motor generator sets they could be ingested into the machinery and cause considerable damage. [6,7] If the clumps fell on high voltage insulators or became lodged in switching contacts of a power distribution facility, momentary arcing and burn-out could occur. The secondary damage would be a function of the ability of the system to recover from this type of transient condition. If the cloud concentration of large particles were to continue in the near vicinity of high voltage insulators, power connection, or switching contacts, severe damage would result from the sustained arcing and low impedance paths.

A second general class consists of medium sized "lint" particles several centimeters in length. Again the pattern of distribution at high concentrations is limited by the airborne conditions, but these particles could be quite damaging even in small concentrations of the order of a few thousand per cubic meter. The length of individual particles would be sufficient to cause a short circuit or low impedance path to most electrical or electronic circuits. Recent tests [3,4] have reported preliminary data which indicate that these medium sized particles have a minimum effect on power level circuits except in extreme concentrations. Thus consumer products such as toasters can normally be considered as safe from shock hazards, although the possibility of such a hazard has been experimentally demonstrated. Shock hazards are discussed in greater detail in Chapter 12.

Control equipment such as heating and ventilating controls could be disabled by the resultant low impedance paths developed by even medium length fibers if they penetrate the control enclosure. The control circuitry is typically low voltage at the sensing and control side of the circuit. The energy levels are too low to burn out the shorting conditions and the low impedance paths would disrupt the control functions. By the same token, if these medium length particles were to enter the control panels and equipment racks of public service distribution or sub stations great damage could result. The power distribution lines, transformers and switching points may be somewhat immune to this level of fiber, but the control circuitry could be severely disrupted if the fibers penetrate the enclosure and deposit on the low voltage electronic modules or switching points.

The third general size class consists of single fibers of the order of several mm in length down to the micron level. These fibers can be airborne in great concentrations for long distances. The physical characteristics of carbon fibers are such that even large clumps or masses of fiber tend to splinter, becoming a source of these smaller, almost dust-like, particles. Spacings between conductors of printed circuit boards are typically 5 to 100 mils, so that a single fiber bridging two conductor lines can result in a lowered impedance. Depending upon the basic fiber material and the amount of residual insulating binder retained on the fiber this impedance could be from twenty or thirty ohms up to a few thousand ohms.

8.4 QUALITY OF AVAILABLE DATA AND ATTENDANT UNCERTAINTIES

Literally hundreds of experiments have been conducted in the recent past to investigate the potential of carbon fibers to adversely affect electrically energized equipment.[2,6] These have ranged from simple

tests designed to determine whether an item is at all vulnerable to carbon fibers, to highly sophisticated experiments to define critical dosages associated with different levels of failure. Unfortunately, many of these studies were intended to answer specific questions not completely relevant to this national risk analysis. Although they provide us with a basic set of results to guide our thinking, they leave us with numerous unanswered questions for which we must crudely formulate answers. In the following, we discuss some of the problems which we experienced with the data.

In most experiments the time profile of exposure was not defined by researchers. That is, the researchers determined the airborne dosage to which a particular item was subjected, but did not report the specific concentration versus time history which comprised the dosage. Intuitively, one would suspect that an exposure to 100 fibers for 10 seconds in a specific volume might not necessarily produce the same effects as 10 fibers for 100 seconds, regardless of the fact that the dosage in both cases is 1,000 fiber-seconds per volume unit. Thus, this possible concentration versus time effect cannot be fully addressed at present, and our analysis contains the associated uncertainties.

Several types of carbon fiber materials and lengths were utilized by researchers in experiments, and we are aware that differing fiber characteristics can influence results. Scattering in available data is likely to be partially caused by this fact. The scattering is unfortunate because it dilutes our capability to pinpoint specific limits or trends.

In a large number of experiments, researchers only reported the airborne dosage*at which a particular item of equipment definitely fails. They did not necessarily continue work to define whether the unit would fail at a lower dosage, or more ideally, to define what percentage of units might fail at a variety of different dosage levels. Thus, the library of data is simply a spectrum of failure levels, and provides little insight into the probability of failure on a statistical basis.

*The terms "dosage" and "exposure" are used interchangeably.

Much electronic equipment is packaged in normally closed metal cabinets and, if necessary for cooling purposes, has cooling fans and air filters, or louvered areas for convective cooling. These cabinets can be expected to provide substantial protection to internal compartments. However, the library of available data is not always clear as to whether or not a particular item of equipment was exposed to carbon fibers without its casing, or whether the casing was in place. In consequence, there are some uncertainties introduced into our analyses by this occurrence. We may have assumed in some cases that a cabinet was in place when it was not, and vice versa.

The majority of studies utilized virgin material as received by a manufacturer. In an actual accidental release, it is highly likely that many of the fibers will have residual binder on their surface. This binder could modify the effective resistivity and/or the flight and building penetration characteristics of the material.

Almost all studies have concentrated on equipment which was energized while exposed to carbon fibers. The Ballistic Research Lab and Bionetics are conducting experiments to determine whether a piece of equipment will fail when activated, after it was exposed while in a non-activated state. We suspect that the results of experiments dealing with this scenario would highlight the influence of the concentration versus time history of an exposure, and might significantly influence the results of this analysis. Additionally, we suspect that differences would be evident in the vulnerability of horizontally placed circuit boards versus those mounted vertically. Obviously, gravity effects would result in differing amounts of deposition, and such differences would affect the potential vulnerability of the equipment.

Numerous experiments highlighted the unpredictability in effects of carbon fibers, and further complicate our understanding of expected phenomena. In some experiments, a few fibers were successful in bridging a critical pair of contacts in an integrated circuit, while a heavy coating of fibers on the same circuit caused no problems.[5] Results such as these promote concerns about any set of experimental

data that does not involve repeated experiments under identical conditions. Additionally, they complicate the development of a statistical approach for defining failure probabilities as a function of experienced dosage.

Finally, it must be noted that the experiments involved a limited number of equipment types, and often utilized equipment constructed to government specifications. Analogies between such equipment and equipment commonly utilized by the public sector may or may not be completely valid.

8.5 FAILURE RATE MODEL

It is almost certain that a particular airborne dosage of carbon fibers will cause some fraction of exposed units to fail, and some fraction to escape unharmed. Thus, for each type of equipment, there is some probability of failure associated with each dosage. Ideally, one would have sufficient data on hand for each type of equipment to define the curve for probability of failure versus airborne dosage.

In the absence of a sufficient body of knowledge, we find merit in the utilization of the simple exponential model, which is pictured in Figure 8-1.

$$P_f(E) = 1 - \exp(-E/\bar{E})$$

Where:

$P_f(E)$ = probability of failure at dosage E

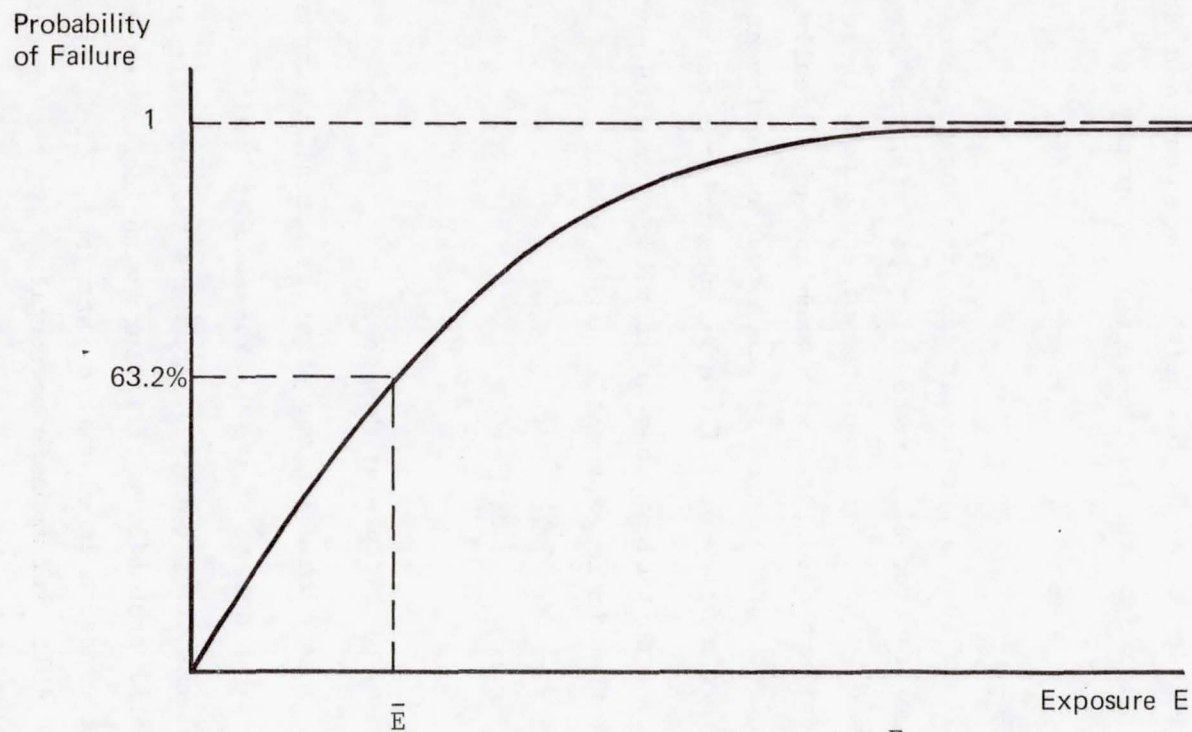
E = airborne dosage to which equipment is actually exposed

$\bar{E}$ = mean airborne dosage at which exposed units fail

The exponential model has the property of constant failure rate - that is, the incremental probability of failure with increasing exposure is independent of the exposure level already attained. Since this model is theoretically plausible, and appears to roughly fit the experimental data (as shown in Figure 8-3), it was selected for use in this study.

FIGURE 8-1

ELECTRONIC EQUIPMENT FAILURE MODEL



$$\text{Probability of Failure} = 1 - e^{-\frac{E}{\bar{E}}}$$

$\bar{E}$ = Mean Exposure for Failure

EXPOSURE	PERCENT FAILURES
$\bar{E} / 100$	1.0%
$\bar{E} / 10$	9.5%
$\bar{E}$	63.2%
$10 \bar{E}$	99.9%

8.6 MAJOR ASSUMPTIONS

Since the data are insufficient individually or in aggregate to resolve the previously discussed uncertainties, a number of simplifying assumptions were necessary. More specifically, we assumed:

- The potential vulnerability of a particular item of equipment is simply and directly a function of the airborne dosage of carbon fibers to which it is exposed, rather than the concentration versus time history.
- The dosage at which a fixed percentage of units will fail is not a function of carbon fiber material type or individual fiber length.
- Equipment was generally tested with casings in place, except where information specifically indicated otherwise.
- No significant differences in results would evolve if non-virgin carbon fiber materials were used in place of virgin materials in experiments.
- It is acceptable to extrapolate results obtained with a limited variety of government equipment to similar equipment in the public sector.
- A non-energized unit will fail when activated if it has previously been exposed to a dosage normally causing failure in an energized unit, and the failure will follow the same probability distribution. (Hence equipment is assumed to be activated.)

We are fully aware that one or more of these assumptions may be in error. In particular, the last assumption will be violated in the case of forced-air cooled equipment, where the activation of a unit significantly increases the transfer rate. Nevertheless, this set of assumptions is appropriate, and indeed necessary, to make best use of the limited body of information currently available.

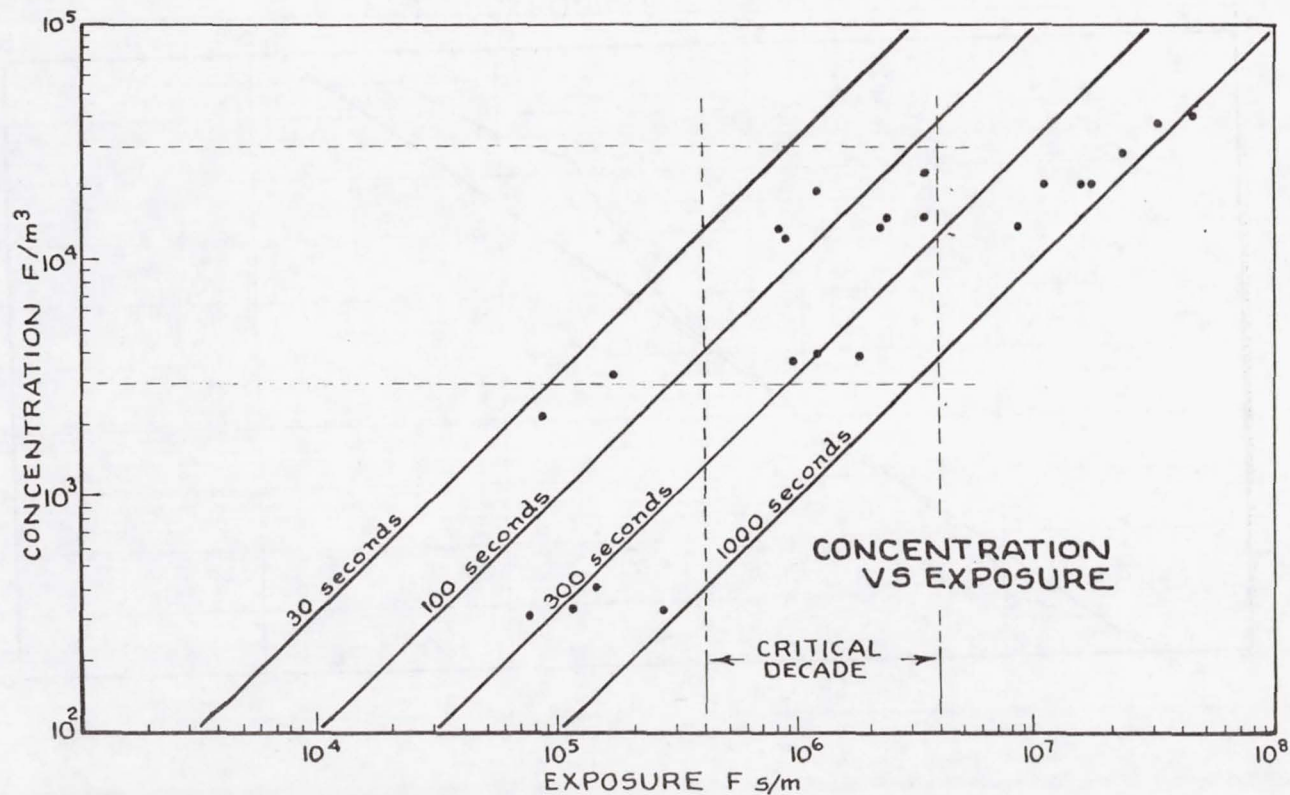
8.7 EXPOSURE AND VULNERABILITY DATA

Carbon fibers in an accidental release will be dispersed in varying size configurations and densities. The majority of field investigations reported have dealt with the effects caused by airborne concentrations of clean fibers of the order of several mm in length. [6] The exposures* were of the order of $1E5$ to $1E7$ FS/M³. In those few experiments where the concentration of the cloud of contaminant and the time to equipment failure were reported, the concentration levels were typically in the range of $0.5E4$ to $0.5E5$. The time periods to failure fell in the range of 30 seconds to five or ten minutes. Only recently have tests been conducted at the extremes of concentration levels under controlled and somewhat repeatable conditions. As of this point in time, few of these tests have been documented in formal reports. The small amount of data that are available substantiate the general trends of earlier tests illustrated in Figure 8-2. From these field data we have developed guideline boundary conditions of exposure that may have a detrimental effect on certain classes of equipment. The results are reported in Section 8.8.

Approximately 511 reported failures were recorded in the literature for electronic equipment ranging from TV sets to computers and motor generator power systems. [2,6] The 511 tests were smoothed and the common equipment categories reduced to mean values. The data were then plotted as a distribution of the exposure versus the percentage of population failed. (See Figure 8-3.) Fifty percent of the units failed at an exposure level of $\leq 8E5$ FS/M³. Sixty-three percent of the units failed at an exposure level of $\leq 1.5 E6$ FS/M³. The aggregated data appear to roughly fit the exponential failure model, but for any one equipment category, there are insufficient data to permit statistical validation of the model.

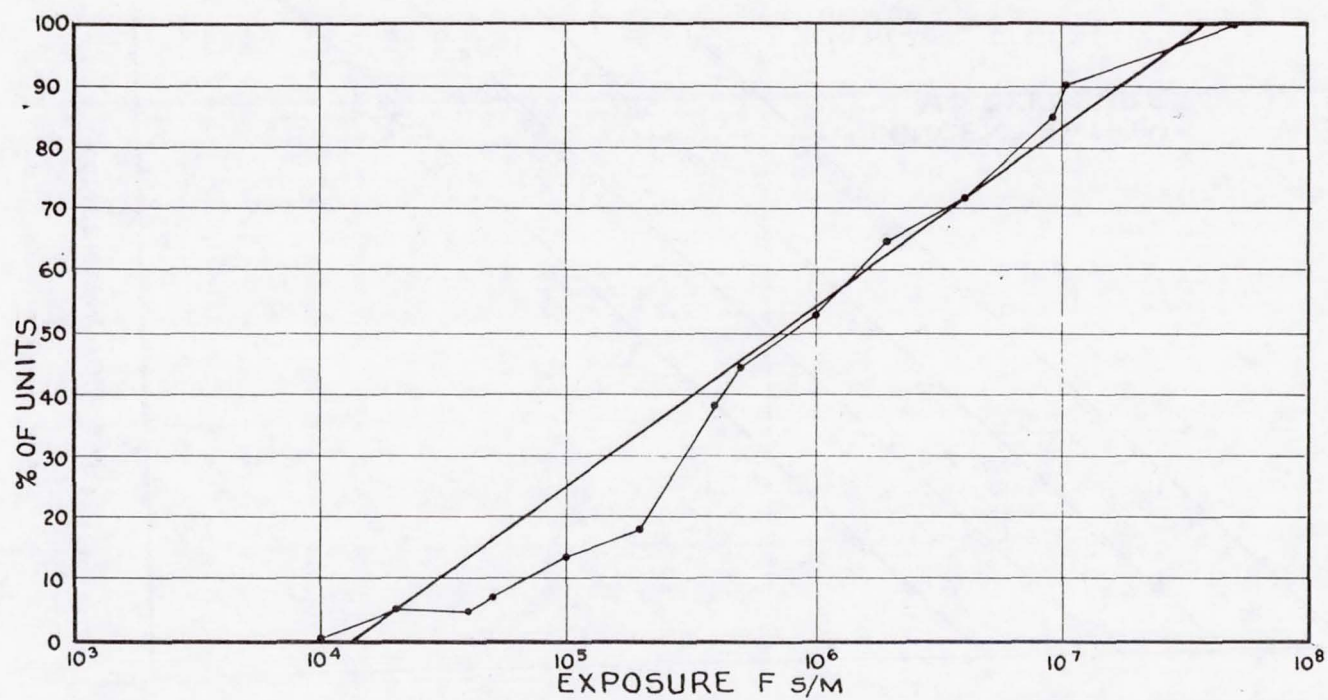
Certain of these data were extracted for which the concentration or time to failure data were available. For the exposure decade around $8E5$ FS/M³ the concentrations ranged from $2E3$ to $3E4$ FS/M³ at a time to failure of 30 to 300 seconds. Less than 15% of the total failures plotted in Figure 8-3 were reported at exposure levels in excess of $1E7$ FS/M³. In

*The notation $1E5$ will henceforth be used to represent 1×10^5 .



GENERAL REPRESENTATION OF CF CONCENTRATION
AND OF EXPOSURE LEADING TO "FAILURE" OF
A VARIETY OF ELECTRONIC EQUIPMENT

FIGURE 8-2



EXPOSURE LEVEL VS PERCENT OF POPULATION FAILED

FIGURE 8-3

the distribution of some of these tests plotted in Figure 8-2, the failures in this category were at concentration levels of 1.5 to 9E4 for periods in excess of 300 seconds. However, all vulnerability estimates developed here will be concerned with exposure only, rather than with concentration and time.

8.8 DATA ANALYSIS RESULTS

We compiled and analyzed the test results for roughly 511 individual experiments. In general, for all types of equipment, it was found that equipment which had a basic potential for failure would regularly fail at dosage levels of 10^8 fiber seconds per cubic meter (FS/M³). At 10^4 FS/M³, failures were relatively rare. For all reported failures, the mean was approximately 8×10^5 FS/M³.

We grouped test results for similar types of equipment classes in an attempt to differentiate between equipment types. Table 8-1 presents the results of this effort. For each generic category of equipment, it notes the number of experiments conducted, the average airborne dosage to failure, and the general range of dosages which caused equipment failures.

The majority of currently available field data on the effects of graphite fibers on electronic equipment are for military equipment. With the exercise of some engineering judgment, these data were extrapolated to certain types of equivalent commercial, industrial and residential equipment. The basis of this engineering judgment is the comparison of such parameters as circuit construction, i.e., use of printed circuit boards, wire wrap, conformal coating and typical conductor spacings; the type of enclosure, i.e., forced circulation, filters, vented openings and typical air flow pattern; and the type of circuitry normally used such as vacuum tube, transistor or integrated circuit as an example. The mean failure levels deduced from such extrapolations are presented in Appendix G. In some cases, these estimates were inconsistent with experimental data which were received too late to be included in the analysis.

TABLE 8-1

EXPERIMENTAL DATA SUMMARY

<u>EQUIPMENT CATEGORY</u>	<u>NUMBER OF TESTS</u>	<u>MEAN DOSAGE FOR FAILURE (FS/M³)</u>	<u>GENERAL RANGE OF CRITICAL EXPOSURE (FS/M³)</u>
Bench Instruments	18	5.9E5	1.3E5 to 9.9E5
Communications Equipment	19	7.6E6	5E4 to 2.5E7
Computer - PDP-8	25	E7	E7
- LS-11	38	4.9E6	5E5 to 2E7
CRT Equipment including			
CRO, PPI, etc.	16	1.5E6	7.1E4 to 3.2E6
Electronic Power Supplies	78	1.5E6	2.1E4 to E7
Motor Generator Equipment	101	9.8E5	2.5E4 to 3.3E6
Rack Mounted Instruments	104	6.1E6	5E3 to 1.4E7
Servo and Relay Equipment	62	2.1E6	1.5E5 to 1.7E7
Television Sets			
B&W	7	6.4E8	7E8 to 8E8
Color	-	1.6E7	1.6E7
Vacuum Tube Equipment	7	6.5E5	6E4 to 1.7E6

Note: 2E7 = 2×10^7 , etc.

8.9 REFERENCES

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2. BRL Report IN78-706 Progress Report on Vulnerability
3. Electrical Circuit Vulnerability
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4. Power Systems Analysis (Secret)
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5. SAR-84 Threshold Susceptibility Criteria (Secret)
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9. ESTIMATION OF ECONOMIC LOSSES

9.1 INTRODUCTION

The dispersion of carbon fibers in the aftermath of an aircraft fire may extend over distances of 80 km. or more, as demonstrated in Chapter 6. If the concentrations of fibers are sufficiently high, a significant possibility exists that a large number of residential, commercial, and industrial establishments might be affected by electronic equipment failure. Since most large and medium hub airports are located in close proximity to heavily populated areas, a significant number of potentially vulnerable facilities fall well within the potential range of a carbon fiber cloud. Thus, estimating economic losses from a carbon fiber release involves characterizing the entire spectrum of buildings and electronic equipment within a given community. Moreover, to fully assess such risks on a national level requires an exhaustive characterization of potentially vulnerable facilities across the nation.

The damaging consequences of a carbon fiber cloud on electronic equipment are mitigated somewhat by the fact that equipment are housed in structures which filter out the fibers. As indicated in Chapter 7, it is difficult to characterize the penetration properties of diverse types of buildings. Even if this were possible, the detailed categorization of equipment found in various facilities and determination of the consequences of equipment failures upon each facility would be an enormous undertaking, well beyond the scope of this study. Therefore, a number of simplifying assumptions have been made to reduce the data collection requirements to manageable proportions. A limited number of facility categories were identified, and assumed to be relatively homogeneous. While variations in facility characteristics within each category were not explicitly considered, the aggregate losses predicted for large numbers of exposed facilities provide an estimate of the magnitude of true economic losses. The detailed examination of potential losses on an industry-by-industry basis will be an important area for future investigation.

9.2 MAJOR ASSUMPTIONS

A damaging carbon fiber exposure at an industrial or commercial facility will produce some degree of economic loss, depending upon the type of equipment damaged and its function in the operation of the facility. Our analysis considers costs of equipment repair, costs of modifying operating procedures, and for critical equipment failures, the costs of a facility shutdown, including the opportunity costs of lost revenue. Because of the limited scope of this analysis, the following assumptions and restrictions governing the assessment of economic loss were necessary.

- We assumed that equipment failure will cause losses associated with the most critical function that the equipment performs in the operation of the facility. The only exception was damage to inventory.
- We assumed that all firms or organizations within an industry have the same financial operating characteristics and revenues, using an industry average for each metropolitan area being considered.
- If several pieces of identical equipment operate simultaneously, failures are independent. Thus, relative locations of equipment do not affect their individual failure probabilities.
- Economics are assessed by category on the basis of statistical expectation, i.e., dollar loss estimates are assigned to the expected number of failures within an industry-equipment category.
- Failures occur within a short period of time after release (hours rather than days) and we are examining a "snapshot" in time shortly after the effects of a release have occurred.

- Within each industry, facilities are identically equipped for each city, and have identical building transfer rates. In certain cases, there may be a distribution of facilities into several transfer rate classes.
- Equipment failures may be classified as critical, disruptive, or repair-only. In a critical failure, the function of the equipment damaged is important enough to cause a shutdown of operations. Thus, costs for lost business, lost expenses and equipment repair were considered. A disruptive failure would not shut down a business but would require that alternate, more costly operating procedures be used. Thus, for disruptive failures, costs of alternative procedures and equipment repair were estimated. A repair-only failure occurs when non-essential equipment fails, and loss estimates were made only for repair costs.
- When a unit of critical equipment fails, the facility is shut down. Thus, the possible presence of redundant systems is ignored.
- Only "primary" costs to the facility in which equipment failure occurred were included. Secondary impacts such as disruptions in the operations of firms relying on a service company which experiences a shutdown, were not considered.

These assumptions make it feasible to estimate economic losses in any major metropolitan area as a function of exposure to carbon fibers. The use of expectations and averages precludes extreme values of loss from being incorporated into the risk profile. However, the other assumptions were made conservative in an effort to ensure that potentially high risks are not ignored in the aggregate, at least for the "primary" types of loss that were considered. The economic losses may be underestimated in cases where either specific facility characteristics result

in unusually high vulnerability, or where secondary impacts upon related business activities are possible. These issues will be the focus of future investigations, as discussed in Section 9.8.

9.3 IDENTIFICATION OF POTENTIALLY VULNERABLE FACILITIES

A potentially vulnerable facility was defined to be any establishment which housed or utilized electronic equipment that might be susceptible to damage from carbon fibers. In addition, equipment exposed to the outdoors, such as aircraft, were considered as a class of facility. Because of the widespread use of electronics in the modern era, potentially vulnerable facilities span the range from industrial and commercial activity to residences and municipal services. Thus, it was necessary to extract a finite set of important facility categories to permit a systematic enumeration of economic losses. Such categories were developed through the following procedural steps:

- Review of literature and experience to determine vulnerable equipment types.
- Preliminary identification of broad SIC (Standard Industrial Classification) categories for investigation.
- Identification of potentially vulnerable equipment categories within industries.
- Field investigations to verify equipment utilization within industries and to verify building penetration estimates.
- Elimination of categories which either had no equipment considered vulnerable or had "white room" facilities to house all vulnerable equipment.
- Assessment of industry-equipment categories as critical, disruptive or repair only.

9.3.1 Review of Literature and Experience

Based on Arthur D. Little experience and a review of the related classified literature, a list of electronic components and types of equipment which could be sensitive to carbon fiber damage was developed. (See Chapter 8). This list served as the basis for a review of SIC industry groups to be considered for economic analysis.

9.3.2 Preliminary Identification of Broad SIC Categories

Based on our knowledge of equipment vulnerability, we defined a list of candidate industries or facilities satisfying any of the following criteria:

- Electronics are produced as finished goods
- Electronic equipment is heavily used in manufacturing or providing a service
- Electronic equipment is used in process control
- Electronic equipment subject to carbon fiber damage is used from a consumer standpoint, e.g., automobiles and households

The final list of categories identified for study is shown in Table 9-1.

9.3.3 Identification of Equipment Categories within Industries

Based on our knowledge of individual industries and the use of industry experts at Arthur D. Little, classes of equipment subject to carbon fiber damage were defined for each industry classifications. This preliminary identification was used as the basis for field work and for the estimation of equipment quantities per facility and repair or replacement costs.

9.3.4 Field Investigations

To verify the equipment-industry classifications and provide better estimates as to the number of units of equipment subject to exposure by industry, field visits were made to numerous sites. Details of the field work are described fully in Appendix B.

TABLE 9-1

FACILITY CATEGORIES FOR ECONOMIC ANALYSIS

- 1 Households
- 2 Police Cars
- 3 Shipyards
- 4 Automobile Radios
- 5 Post Office (major sorting centers)
- 6 Subway, Railroad
- 7 Manufacturers of Power Transmission Equipment (SIC 3568)
- 8 Manufacturers of Electronic Computing Equipment (SIC 3573)
- 9 Telephone Company - Central Switching Facility
- 10 Telephone Companies - Branch Office (SIC 481)
- 11 Radio, Television, Communication Services (SIC 483, 489)
- 12 Gas and Electric Utilities (SIC 491, 492, 493)
- 13 General Merchandise Retailers (SIC 531, 56, 57, 59)
- 14 Retail Grocers (SIC 541)
- 15 Financial and Insurance Institutions (SIC 602, 612, 63)
- 16 Business Services (SIC 73, except 737, 7391)
- 17 Computer Programming, Software Services, Data Processing (SIC 737)
- 18 Electronic R&D Labs, Universities, Colleges (SIC 7391, 822)
- 19 Hospitals (SIC 806)
- 20 Airplanes at Airports
- 21 Airport Control Tower
- 22 Airport Terminals
- 23 ASR Field Radar at Airport
- 24 LOC at Airport
- 25 VOR at Airport

9.3.5 Assessment of Failure Consequences

Based on the field work and our knowledge of industrial processes, equipment-industry categories were classified according to the consequences of a failure. Three classes were used: critical, indicating a shutdown of the facility; disruptive, indicating that alternative procedures are required; or repair only, in which the only economic loss is due to equipment repair. These classifications are shown in Appendix G for each of the 25 facility categories.

9.4 ENUMERATION OF EXPOSED FACILITIES

The development of a national risk profile requires that we examine those airports which account for the majority of the air traffic in the United States. According to FAA Airport Activity Statistics, 68% of passenger enplanements occur at 26 large hub airports, while an additional 40 medium hubs account for another 16% of the enplanements. These 66 airports were selected for specific attention in both the analysis of accident probability (Chapter 4) and the estimation of economic losses. For each of the facility categories in Table 9-1, it was necessary to enumerate facilities in the vicinity of the major U.S. airports. This enumeration was performed by two methods:

For each of the 66 large and medium hub airports, postal zip codes were obtained for the area surrounding each airport within an eight-kilometer radius. For each zip-code, counts were obtained [1] of the total number of businesses in ten broad classifications:

- Agriculture
- Mining
- Contracting
- Manufacturing
- Transportation
- Wholesale
- Retail
- Financial
- Service
- Government

The number of households was also recorded. These data were intended as the primary basis for the extrapolation of economic loss profiles to the 40 medium hubs, as described in Chapter 11.

To obtain coverage of a larger area, we used 1972 or 1975 census data by SMSA and county for both households and businesses. (A complete list of the data sources for each of the 25 facility categories is given in Appendix G.) These data formed the basis for the risk analysis of the 26 large hubs, as described in Chapter 9. Using detailed area maps, facility counts were allocated to various geographic sectors within an 80-km. radius of each large hub.

The area surrounding the center of the airport was divided into a series of concentric circles, bisected by diameters, to form a polar coordinate map as shown in Figure 9-1. The radii of the circles are 8, 16, 32, 56, and 80 km. The diameters bisect them at 45° intervals, creating 40 geometric sectors. Portions of the airport which lie in the eight sectors surrounding its center, were allocated based on physical position from detailed aviation charts. Thus, runways may fall in a different sector than terminal buildings. An example of the sector map surrounding Boston's Logan airport is shown in Figure 9-1.

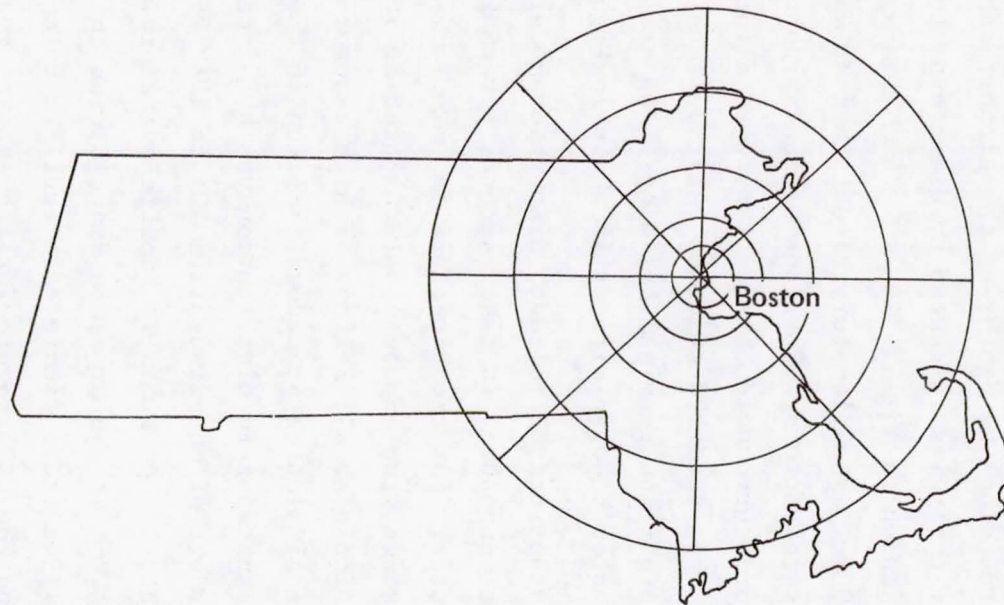
For each hypothetical CF release, dispersion models were used to calculate the fiber exposure, in fiber-seconds per cubic meter, at four points in each sector. For those sectors in which the main trajectory of the CF cloud was contained, the exposure was computed at 100 points to identify the location of small regions of high exposure. (A thorough description of the simulation procedure is given in Chapter 10). Based on these results, an exposure distribution was obtained for each sector, ranging over 10 orders of magnitude from 10^1 to 10^{10} fiber-sec./m.³. It was assumed that the fractions of facilities receiving different levels of exposure were given by the exposure distribution in that sector. By aggregating over all sectors within each facility category, we then obtained a distribution of exposure for the entire area.

9.5 COMPUTATION OF EXPECTED NUMBER OF EQUIPMENT FAILURES

For each industry-equipment category, the number of units of equipment per facility was estimated as explained in Section 9.3. The expected number of pieces of equipment which fail in a given firm for an industry-equipment category was computed using the failure probability distribution for

FIGURE 9-1

DISTRIBUTION OF SECTORS AROUND LOGAN AIRPORT, BOSTON, MASS.



the type of equipment, the outside carbon fiber exposure, and the transfer rate for the building housing the equipment. (Failure probabilities are discussed in Chapter 8, and the transfer rates in Chapter 7.)

The outside carbon fiber exposure at a facility within a sector is determined by the characteristics of the hypothetical accident and the resulting dispersion of fibers. For each industry classification, inside exposure was calculated by multiplying the outside exposure by the transfer function for the facility in question. In most cases, a variety of building types were specified for a given industry, each with a different transfer function range based on the characteristics of the construction and ventilation systems. The distribution of buildings by industry classification is given in Appendix G. Estimates of the proportion of building types for each industry grouping were based on field investigations and in-house industry knowledge.

Once an inside dosage had been calculated, the possibility of failure for each unit of equipment was determined, based on the exponential failure model described in Chapter 8. The expected number of pieces of equipment which fail is equal to the probability of failure for one item, multiplied by the number of pieces of equipment in industry-equipment category. Independence among unit failures was assumed, so that the relative locations of different units did not affect their failure probability.

The building characteristics of each industry category are expected to vary over the metropolitan area surrounding each airport. However, such variation does not necessarily lead to differences in transfer rates. For example, households in downtown areas are a mix of very old and very modern buildings, of which the latter are more likely to be air conditioned. In colder weather when windows are closed, however, the transfer rates are similar for nearly all residential structures. Moreover, in warmer weather the mix of open windows and air conditioned apartments downtown tends to be quite similar to the mix of open and closed windows in suburban homes. Similarly, the differentiation of building types by sector for industrial facilities is also not readily apparent. Thus, we assumed uniform transfer rates throughout all sectors.

Even though transfer rates would be expected to vary between different cities, our field surveys (Appendix B) did not reveal any substantial differences within industry categories. In general, the variation of building characteristics within an industry far outweigh differences due to climate or geography. Thus, we applied the same transfer rates and distributions of building type across the nation. As a result, the expected number of failed units per facility depends purely on external CF dosage.

9.6 COMPUTATION OF LOSSES DUE TO EQUIPMENT FAILURE

Failures of equipment of a given type within each industry were classified as one of three types: critical, disruptive, or repair only. Computation of economic losses are different for each and are discussed in this section, along with the methods used to aggregate the total loss into a risk profile.

9.6.1 Losses for Critical Failures

A critical failure has been defined as one which causes a temporary shutdown of a business. Therefore, to estimate losses one must consider lost revenue in the case of service industries, value added in the case of manufacturers, and the cost of repair to the damaged equipment.

Value added is the appropriate measure of loss when intermediate goods are converted into finished goods. In this situation, the total revenue figures would include second order impacts upon suppliers of intermediate goods, which we did not include in our analysis. For example, the value added in the case of an automobile manufacturer is the revenue from automobile sales minus the cost of the automotive parts and components purchased from suppliers.

Economics were estimated on the basis of the expected number of critical facilities to be affected. This expected number was computed as a result of the expected number of pieces of critical equipment which fail, assuming independence in the failure probability for each piece of equipment. In this analysis, we have assumed that if any one piece of equipment fails, the facility is shut down. This assumption is conservative in that it ignores the possibility of emergency or backup equipment which would permit the facility to continue operation.

Under the assumption that critical equipment can be repaired or replaced within one day, which ADL industry experts feel is realistic, we have used a one-day shutdown in our evaluation of lost revenues. These revenues, or value added, were estimated from financial data for each facility class, divided by 250 working days per year. Appendix G.4 lists the detailed sources of these data.

Repair Costs, which are separate from the costs of shutdown, were estimated for each industry-equipment classification. These costs are also detailed in Appendix G and are generally on the order of magnitude of 10% of the installed value of the equipment. Estimates for losses due to failure of major equipment, such as telephone switch gear, are subject to future refinement through more detailed investigation.

9.6.2 Losses for Disruptive Failures

A disruptive failure has been defined as one which causes a business to alter its normal operating procedures to accommodate the failure of a non-critical component or piece of equipment normally used. Thus, losses due to more inefficient and costly procedures must be considered and added to repair costs in the economic assessment.

Economics were estimated on the basis of the expected number of facilities affected by disruptive failures. Under the assumption that a disruptive failure has 10% of the impact of a shutdown with regard to revenue losses, the computation is basically the same as that for a critical failure. Overtime costs were not quantified explicitly but were assumed to be included in the 10% figure.

Four types of data are necessary for the above analyses; the number of facilities, the economics of a facility, the distribution of equipment within a facility and the cost of repair for equipment. For each airport investigated, data were gathered regarding both the number of facilities and economics of facilities in the area. Data on the distribution of equipment within a facility were, with the exception of airports, assumed to be constant nationwide. Repair costs for equipment were gathered on a per-piece basis and also assumed to be uniform nationwide.

For each city, losses were estimated in each industry-equipment category based on the exposure simulation and summed through simple addition. These results were used in the construction of the national risk profile, as described in the section on simulation methodology in Chapter 10.

9.7 APPLICATION OF ECONOMIC ANALYSIS TO FACILITY CATEGORIES

This section briefly outlines the analysis performed for each of the twenty-five facility categories shown in Table 9-1.

1 Households

The equipment determined to be at risk in the average household consists of televisions and stereos, white goods(i.e. kitchen appliances), and furnace controls. The only economic loss for a household is the repair cost of the equipment. Several household building types were analyzed for building penetration rates, the primary distinction being whether windows were open or closed.

2 Police Cars

Study of the police indicated that the only equipment possibly at risk were police car radios.* Therefore, economic losses were restricted to the repair of the radios. Indirect costs of reduced police services were not considered in the analysis.

3 Shipyards

Equipment at risk in shipyards include mini-computers, electronically controlled cranes, and computer terminals. Because of the nature of shipyard operations, it is highly conjectural to assign a loss of revenue to the failure of this equipment during the time required for repair. Therefore, only repair costs were included.

4 Automobile Radios

Equipment at risk for automobiles are restricted to radios* for which only repair costs were considered.

*Recent studies by BRL indicate that car radios may not be as vulnerable as originally suspected.

5 Post Office

Major Post Office sorting centers have two types of mini-computer controlled letter sorters: Optical Character Readers and more conventional manual read machines. Failure of equipment for a short period of time would result in delayed service but no revenue loss or cost increases of significance. Therefore only repair costs were considered for this category.

6 Subway, Railroad

The primary equipment at risk are the radios on board subway and commuter rail cars. For the Boston subway system, more extensive data were available and additional categories considered. The equipment at risk is not crucial to operations and its failure would at worst lead to temporary delays in service. Therefore only repair costs were considered.

7-17 Manufacturing, Retailing, and Service Business

For each of these categories a set of support type equipment were identified. With only one exception, work-in-process inventories and finished goods were assumed to be invulnerable to carbon fiber penetration, due to normal cabinet filtration and/or protected manufacturing environment, according to our field investigations. The single exception was category 8, computer manufacturers, where work-in-process is potentially at risk. There are two categories for telephone companies, categories 9 and 10, to differentiate PBX systems at branch offices from centralized facilities for large metropolitan areas. The centralized facilities do not show critical losses because revenue losses are recognized at the branch level in our analysis. Telephone company branch office repair costs for PBX systems were calculated as follows, based upon ADL industry knowledge:

Repair Cost = 10% of installed cost

Installed Cost = \$1000 per line

There are 13,000 lines on average in each Bell System branch office. The repair cost for main switching centers is based on the cost of repair for the 1975 New York City fire. [6]

18 Electronic R&D Labs, Universities, Colleges

In these institutions, scientific and support type instrumentation is at risk. Equipment failures would lead at worst to activity delays ; thus, only repair costs were included.

19 Hospitals

Several categories of support equipment were included for hospitals. While in rare instances some combinations of equipment failures would put human life at risk, probabilities of such occurrences could not clearly be identified because of various backup procedures. Similarly increases in direct costs resulting from failures could not clearly be identified. Therefore, only repair costs were included in the economic analysis.

20 Airplanes at Airports

Three categories of equipment were identified for airplanes which are potentially at risk. If the avionics equipment fails during normal pre-flight check-out, the flight will be delayed and most likely cancelled. Revenue per flight losses was estimated using an average fleet mix and load factors.

21-25 Equipment at Airport

These five categories were tabulated individually for more accurate identification of the location of equipment with respect to the release site and resultant carbon fiber dispersion. Economic losses beyond repair of equipment were not identified because of the difficulty in assessing the impact of one or more navigational or ATC facility failures, given the elaborate backup procedures in the airspace system.

9.8 AREAS FOR ADDITIONAL INVESTIGATION

The economic analysis presented above takes a broad-brush approach at representing the potential losses across all civilian segments of society due to a carbon fiber release. The major weakness of this approach is the treatment of facilities within an industry as being homogeneous in size, operating characteristics, protection against fiber penetration, and use of electronic equipment. This assumption leads to an expected-

value approach for calculating total loss within an industry, and may, therefore, neglect the gradations in the features and the differences in risk among facilities. The Monte Carlo simulation approach is capable of incorporating such differences, provided they can be documented and input. Thus, if additional investigation of economic impacts is performed, it may be possible to refine the economic analysis and to produce a risk profile more sensitive to the heterogeneous nature of exposed facilities. Several areas merit further effort:

9.8.1 Improvement of Facility Categorization

The facility categories exhibited in Table 9-1 may be examined in greater detail, to determine whether further divisions are warranted, whether certain categories may be omitted, and whether additional categories need to be considered. Such a review should be based upon penetration and vulnerability criteria, as well as a more fine-grain description of industrial and commercial activities. Once the set of categories has been established, each one should be examined from a micro-analytic perspective. This would require field visits to several different facilities within the same category.

9.8.2 Detailed Equipment Failure Analysis

The types and numbers of equipment in each facility may be described in greater detail, and will probably vary considerably from one facility to another. A failure analysis may be performed for several typical facilities, using techniques such as fault trees, to determine possible modes of economic loss. These modes could replace the broad categories of critical, disruptive, or repair-only failures. Furthermore, the probabilistic analysis of failure incidence should be expended to account for locations of equipment, special protective measures, and the possible presence of backup units.

9.8.3 Refinement of Cost Estimates

The financial burden to a facility in which failure occurs may be investigated more explicitly, by selecting different failure scenarios and examining their effects on operating costs, revenue, and profit.

Again, this would require identification of several different facilities, spanning a range of features such as age of design, complexity of industrial processes, and overall size of the operation. Costs of clean-up after exposure, preventive measures, overtime wages and interrupted business may then be specified more precisely.

9.8.4 Inclusion of Secondary Losses

The most challenging area for economic analysis is the assessment of secondary losses to society at large incurred by the failure of a particular facility. Examples of this phenomenon are interruption of telephone service due to a telephone branch office breakdown or the loss of transportation due to failure of a subway control box. Such scenarios, which require a thorough investigation of the potential impacts, may be difficult to quantify accurately.

9.9 REFERENCES

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10. MONTE CARLO SIMULATION OF SINGLE ACCIDENT AIRPORT RISK PROFILE

10.1 INTRODUCTION

A computer simulation model has been developed for estimating the potential economic impacts of a carbon fiber release upon facilities within an 80-kilometer radius of a major airport. Assuming that an air carrier incident or accident involving fire or explosion has released carbon fibers, the model simulated the possible range of release conditions and the resulting dispersion of the carbon fibers. Each iteration of the model generated a specific release scenario, which would cause a specific amount of dollar loss to the surrounding community. By repeated iterations, a risk profile was generated, showing the probability distribution of losses from one accident. Using accident probability estimates, the risk profile for annual losses was derived. This chapter describes the mechanics of the simulation model, the required input data, and the risk profiles generated for the 26 large hub airports.

The above procedure provided a means of generating a distribution of losses, conditional on there being an accident at a given airport. This was part of a multi-step procedure used for computation of the national risk profile. The first step was to generate the conditional risk profile of each of the individual airports. The second step was to synthesize these distributions into a single distribution that was again conditional on there being an accident. In the final step, the national probability of an accident was combined with the conditional national risk profile to generate an unconditional profile.

In the course of this approach, two different representations of risk were generated. The first was a loss-per-event profile, which showed the annual frequency of a given loss resulting from a single incident. The second type of profile presented the probability of accumulating annual losses of a given amount. The differences between the two types of risk profiles was that the latter type of profile described the potential total losses resulting from one, two, or more incidents or acci-

dents, while the former simply shows the frequency of occurrence of an accident with a given loss. To generate the former type of risk profile, probabilities in the conditional risk profile were multiplied by the annual frequency of accidents. (For example, if the probability of a million dollar loss were once per thousand accidents, and there were on average two accidents per year, then the frequency of million dollar accidents would be two in a thousand per year.) To generate the latter type of risk profile a special mathematical convolution procedure was performed. This procedure is described in Chapter 11, along with a presentation of both types of risk profiles. The emphasis in this chapter is on the development of the conditional risk profiles for the 26 major airports.

10.2 DESCRIPTION OF SIMULATION PROCEDURE

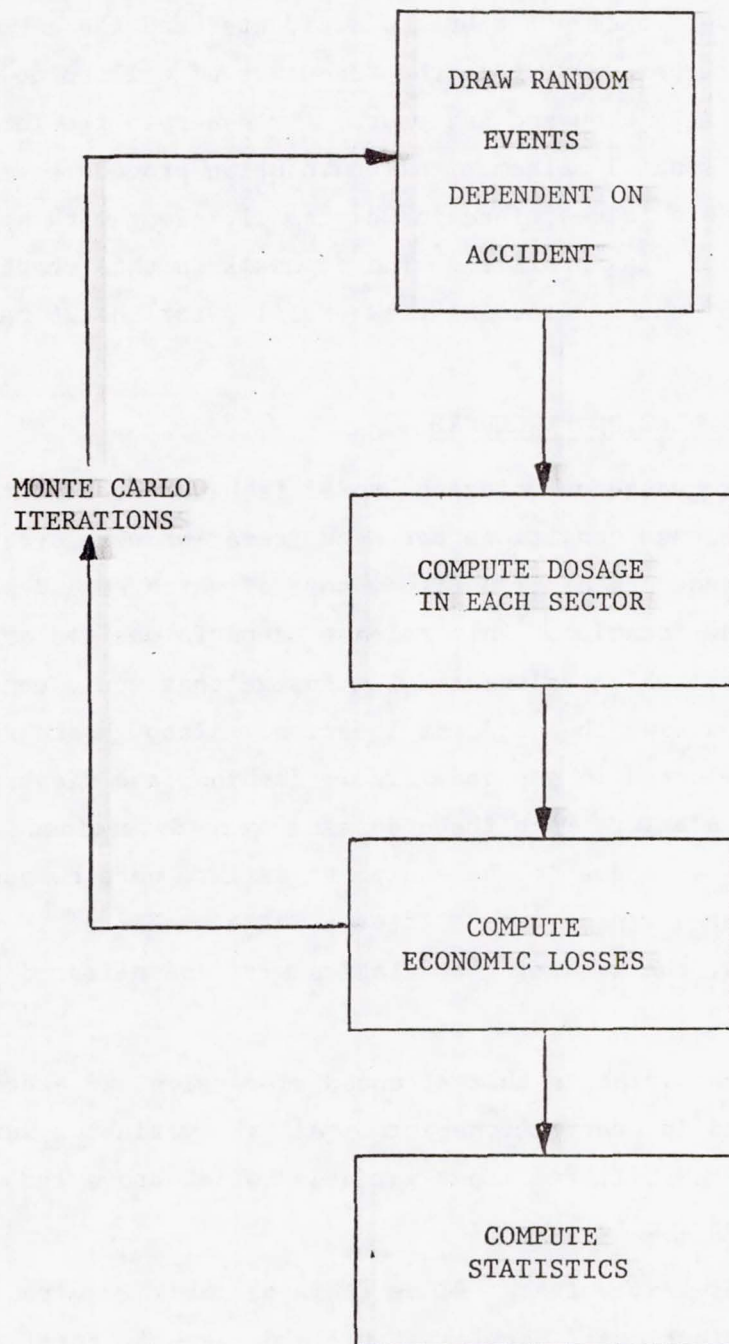
The Monte Carlo procedure on which the model is based is summarized in Figure 10-1. The release conditions for each iteration were determined by random draws from frequency distributions, some of which were dependent on the accident type and location. This release scenario was fed as input to a dispersion model which calculated the dosage that would occur at various points surrounding the accident location. Although the release scenarios were selected in a probabilistic fashion, the dispersion calculation was deterministic. Once these dosages were determined, direct and indirect economic losses due to the equipment failure were computed on the basis of aggregated census data. After a large number of iterations had been recorded, the resulting statistics were consolidated to produce a risk profile.

Descriptions of the variables that affected dispersion and economic loss have been presented in previous chapters. All the variables were dependent on a set of probabilistic input variables which drove the model. These variables included the following:

- Type of Release - Explosive or Plume (this variable required two input distributions: One for static and take-off total destruction accidents; another for all other accidents.)

FIGURE 10-1

OVERVIEW OF MONTE CARLO PROCEDURE

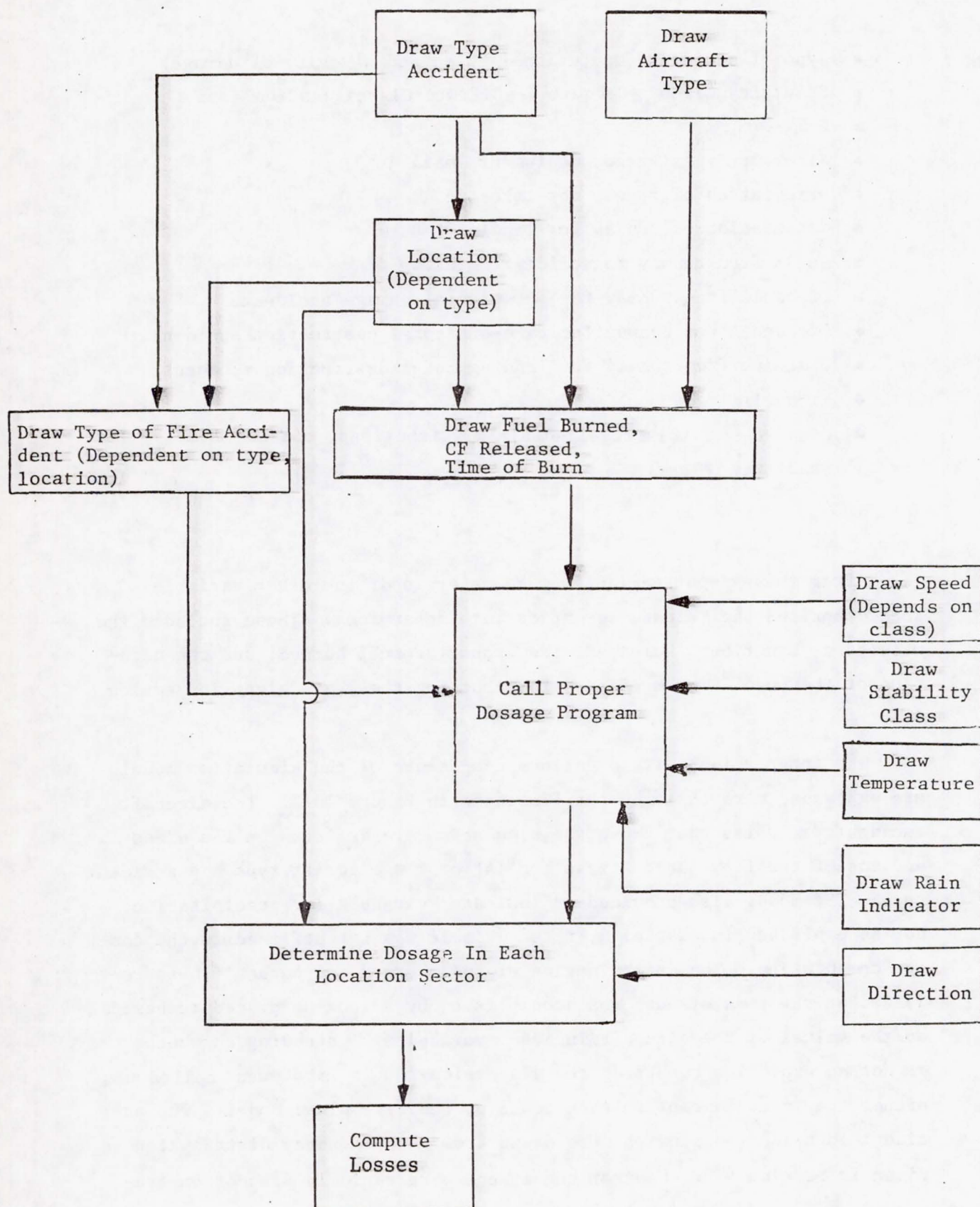


- Type of Accident (Operational Phase and severity of damage)
- Stability Class (Pasquill - Gifford Classification)
- Temperature
- Aircraft Type (Large, medium or small jet)
- Orientation of runway for take-off
- Orientation of runway for landing
- Angle from runway to accident location
- Distance from runway for substantial damage accidents
- Distance from runway for take-off total destruction accidents
- Distance from runway for landing total destruction accidents
- Wind Direction
- Wind Speed (this required six distributions, one for each stability class)

After these input variables were determined, the other variables that comprised the release scenarios were determined. These included the mass of carbon fibers released, the amount of fuel burned, and the duration of the burn. The mechanics for choosing these are given in Section 5.3.

The interactions of the various components of the simulation model are explained more fully by the flowchart in Figure 10-2. The aircraft incident variables that drove the simulation are depicted on the sides and top of the flowchart; these consist of the aircraft type and accident type. The model also provided an indicator variable for precipitation, but as explained in Chapter 5, this variable was not utilized in the dosage computation. The determination of fuel burned and carbon fibers released at the time of burn was accomplished by a look-up procedure based on the values of the aircraft/incident variables. Depending on whether or not an explosion occurred, the dispersion routine that was called was either the instantaneous release model or the fire plume model. The accident location coordinates were drawn from the frequency distribution given in Section 4.5. Weather conditions were randomly drawn from fre-

FIGURE 10-2
MONTE CARLO SIMULATION PROCEDURE



quency distributions specific to the city being modelled.

To initiate the dosage calculations, the area surrounding the center of the airport was divided into a series of concentric circles bisected by diameters to form a polar coordinate map, as shown in Figure 9-1. Thus, forty geometric sectors were defined. The procedure for determining the dosage distribution in each sector involved repeatedly evaluating dosages at individual geographic locations within these sectors. Such a procedure required a large number of dosage calculations within the simulation, and therefore an efficient procedure was needed to rapidly compute dosages. This procedure was accomplished in three steps:

1. For each point at which a dosage is to be computed, the distance along the major and minor axes of the dispersion cloud were computed.
2. At the beginning of each Monte Carlo iteration a series of major axis dosage computations were performed (31 computations) and stored in an array to facilitate a table look-up computation of the dosage for any given point.
3. The minor axis computation dosage was performed directly by formula.

For each of the 40 sectors in the geographic model, dosages were calculated for 4 points uniformly distributed within the sector. The sector with the maximum dosage found was flagged. Dosages were then computed for 50 additional points in the five sectors lying in the same direction as the sector of maximum dosage. The 50 points were determined by a fivefold subdivision of each sector along the radial direction and a tenfold subdivision along the angular direction. (In examining several test cases we noted that the variation of dosage along the radial direction was low but the variation along the angular was very high.) After the exposures were computed along these lines, the percentage of geographic area in each decade corresponding to dosages from 10 to 10^{10} fiber-seconds per cubic meter was computed. These percentage distributions were used directly to calculate economic loss. The final part of the simu-

lation was the computation of economic losses in each sector of the metropolitan area.

The number of facilities in each sector was obtained from census data from each city, classified by facility categories. It was assumed that the fractions of facilities receiving different levels of exposure were given by the exposure distribution in that sector. Then, by aggregating over all sectors within each facility category, we obtained a distribution of exposures for the entire area. The computation of number of failures and dollar losses was based directly upon the distribution of exposure for each facility category in each city. The mechanics of this computation, which involved building penetration and equipment failure rates, were presented in the chapter on the economic analysis, Chapter 9.

10.3 SIMULATION RESULTS FOR THE LARGE HUB AIRPORTS

The national risk profile was based on the simulation of the 26 U.S. hub airports as defined by the F.A.A. (See Section 2.5). For each of these airports a set of input data was developed for the simulation. These input data consisted of

- Probabilistic inputs common to all of the airports
- Probabilistic data unique to each city
- Non-probabilistic data such as facilities data for each sector

The probabilistic data common to each airport consisted of the following:

- Probability of explosive release
- Accident type distribution
- Distribution of angle from runway
- Distribution of distance from runway

Probabilistic data unique to each city included

- Aircraft mix
- Runway orientation distributions
- All weather distributions

The non-probabilistic data consisted of two parts: The first part was the location of the terminal buildings. We conservatively assumed that static accidents would take place at these locations at each of the airports.

The second part of the non-probabilistic data was the body of economic data described in Chapter 9. These included:

- Number of establishments by category in each geographic sector
- Average revenue loss for critical equipment
- Equipment failure levels
- Building transfer functions

As explained in Chapter 9, the data on number of establishments were unique to each city while the remainder of the data were common to all of the cities. To obtain conservative risk profiles, the building transfer functions were set at their maximum values.

The conditional economic loss profiles for the twenty-six hub airports constituted a major intermediate result in our risk analysis work. These conditional profiles are presented in Table 10-1. For each major hub, the mean, standard deviation, and selected percentiles of the distribution are presented. The minima and maxima represent the sampled minima and maxima for the simulation. There were 300 iterations of the simulation model performed for each city. Statistically, the minimum and maximum of a 300-iteration simulation run represent percentiles corresponding to probabilities of 1/301 and 300/301 respectively. We therefore assumed these percentiles in the synthesis of the national profile.

There are several observations worth noting in these conditional profiles. First the distributions are all skewed. That is, the tail corresponding to losses larger than the median is more extended than the tail corresponding to losses less than the median. This is emphasized by the fact that the standard deviations of these distributions are greater than the means.

The maximum losses for most of the cities are between one and ten million dollars. Although there is no strong correlation, the largest

TABLE 10-1

CONDITIONAL RISK PROFILES FOR 26 HUBS

(Dollar Losses with 1993 CF Use)

	MEAN	STANDARD DEVIATION	MINIMUM	5 PCT	10 PCT	25 PCT	50 PCT	75 PCT	90 PCT	95 PCT	300 PT. MAXIMUM
Atlanta	83,194	123,640	0	2	57	1,472	25,958	123,980	261,550	363,510	724,270
Boston	119,890	268,220	0	0	0	0	1,648	209,660	361,060	508,250	3,142,500
Chicago	186,090	306,850	0	147	349	7,206	141,160	227,680	405,270	591,770	2,815,300
Cleveland	106,240	235,190	0	44	94	784	9,610	107,810	358,960	610,560	1,893,500
Dallas	9,072	21,018	0	0	0	31	743	6,391	28,712	46,114	143,050
Denver	102,820	280,080	0	0	0	577	11,476	66,421	261,930	475,290	2,607,600
Detroit	55,176	73,335	0	0	352	4,009	39,695	81,119	122,430	166,520	685,300
Honolulu	95,244	148,920	0	0	0	501	71,967	157,930	204,810	289,010	2,040,500
Houston	14,594	47,967	0	0	0	13	749	6,404	36,465	78,791	573,940
Kansas City	4,071	7,180	0	33	305	990	2,004	4,589	8,004	11,129	75,629
Kennedy	156,730	295,740	0	10	159	1,128	45,800	190,940	413,590	633,150	2,409,400
LaGuardia	268,630	588,530	0	287	747	2,999	56,754	347,540	697,670	1,176,400	6,458,300
Las Vegas	43,008	91,718	0	17	272	3,193	7,205	23,750	137,130	223,330	560,990
Los Angeles	371,530	933,150	0	0	0	0	6,581	212,340	1,319,400	1,964,800	9,019,400
Miami	109,480	290,310	0	0	0	1,529	42,774	153,840	238,930	328,230	4,270,000
Minneapolis	178,760	473,280	0	0	0	19	4,157	210,530	519,730	943,040	6,305,300
Newark	217,050	298,780	0	0	634	2,886	88,302	315,170	598,770	951,540	1,459,000
New Orleans	36,256	123,160	0	0	48	150	1,943	22,514	68,978	155,600	1,382,600
Philadelphia	184,100	510,040	0	173	422	1,507	30,757	114,380	534,030	1,042,300	5,124,500
Pittsburgh	83,457	144,110	0	86	250	1,898	20,033	109,630	273,810	393,080	1,004,000
Phoenix	47,826	134,910	0	0	0	0	360	19,741	138,140	314,530	1,077,600
San Francisco	59,577	109,700	0	0	0	98	869	82,329	224,440	278,510	750,020
Seattle	77,848	141,490	0	7	73	682	17,249	110,070	217,290	308,290	1,500,000
St. Louis	74,399	130,300	0	126	263	4,332	33,608	83,897	187,530	237,590	1,045,700
Tampa	37,632	74,918	0	0	27	263	4,769	37,303	118,700	186,770	530,310
Washington	107,130	285,920	0	90	210	1,354	25,211	103,330	217,120	436,470	3,045,000

losses appear to be characteristic of the largest cities. For cities where the airport is close to populated areas (e.g., Boston, Los Angeles, New York) losses were also high. We did not, however, do an extensive analysis of the relationship between loss profiles and city characteristics. Some correlation analysis is described in Chapter 11 in the discussion of extrapolation to medium and small hubs.

There was some question regarding maximum values obtained from the simulation. For any given city, a loss higher than the maximum could conceivably occur. In order to develop a confidence bound for the probability of a loss higher than the maximum observed, we utilized the binominal probability distribution. Suppose that the probability per accident of a given loss is λ . Then, using the binominal distribution the probability of not observing any such losses in 300 simulation trials is

$$(1 - \lambda)^{300}$$

To determine a 95% confidence bound, we set the above expression equal to 5%, which yields a value of $\lambda = 1/100$. Thus, the 95% bound is 1/100.

(A Poisson approximation to the binominal also yields the same result.)

For the national profile, however, a stronger statement can be made, and this is discussed in Chapter 11.

10.4 SENSITIVITIES AND HIGH LOSS INCIDENTS FOR THE INDIVIDUAL CITY PROFILES

After developing the profiles for each of the 26 cities, we examined the sensitivities in these profiles with respect to key variables, as well as the combination of factors that resulted in high loss incidents.

In examining the release scenarios of the accidents that resulted in high economic losses it became clear that the weather conditions had a greater effect than the aircraft conditions. In particular, the size of the plane and type of accident did not seem to have a great bearing on the economic loss. However, the high loss cases for each city were

generally characterized by a small set of wind directions; Many of the high loss cases were for medium or small planes and some were substantial damage accidents. Hence, the key variable seemed to be the direction of the release. In examining test cases, it was noted that the dispersion clouds had very narrow widths implying that high loss cases were determined by the locations of vulnerable facilities. This fact is consistent with the existence of key directions in each of the city simulations. A few high-cost cases are listed in Table 10-2.

Note that four out of the five high cost cases in Table 10-2 are explosive releases, whereas, only 9% of the simulated accidents resulted in explosive releases. While explosive releases seem to be important in explaining the extreme high losses, these five cases in Table 10-2 were not representative of other high cost cases. There were many plume release accidents resulting in losses between one million and five million dollars. The incidence of explosive releases was important in increasing dollar losses, to the degree indicated by the table.

The above observations concerning the high risk cases were confirmed by the sensitivity analyses performed on three of the relatively high-loss cities, Boston, Newark, and Los Angeles. Table 10-3 shows a compilation of these sensitivity analyses. The first row examines the effect of fairly substantial changes in burn times and carbon fibers released. The third row examines the effects of aircraft size and accident types by considering only large plane, takeoff total destruction accidents. The second row examines the same factors but also considers 100% explosive releases rather than the 9% mixture in the original run. The final three rows examine the effect of changes in the transfer functions and of 1985 usage of carbon fiber composites.

Some of the sensitivities show substantial increases in dollar losses, although less than an order of magnitude. The first row shows that losses can increase when the amount of fibers released increases by a significant amount. The original CF release quantities ranged from 23 to 517 kg., as shown in Table G-2. Restriction of input to takeoff

TABLE 10-2
HIGH COST CASES
(ABOVE \$5 MILLION)

City	Total Cost	Residential Cost	Phase	Level of Damage	AC Size	Type of Release	Atmosphere	Distance From Airport Center	Wind Direction	Speed	CF Mass (kg.)	Time of Burn	Fuel (kg.)
Los Angeles	9.02 million	3.5 million	Takeoff	Total	Conventional	Explosion	C	1-1/2 miles ENE	NW	3.1	170	30 min.	19,200
Los Angeles	6.88 million	2.7 million	Static	Total	Conventional	Explosion	C	--	NNE	1.97	170	4 min.	1,920
Laguardia	6.46 million	3.36 million	Takeoff	Total	Conventional	Explosion	C	--	SE	1.39	170	4 min.	6,420
Minneapolis	6.31 million	1.92 million	Takeoff	Total	Large	Explosion	B	--	N	1.06	513	4 min.	25,700
Philadelphia	5.12 million	1.62 million	Landing	Total	Conventional	Plume	B	--	NWE	4.4	68	4 min.	1,920

total destruction accidents and large planes increased the distribution of losses, but not to any great extent. A comparison of the second and third rows measures the sensitivity of losses when explosive releases are increased from 9% to 100% of the accidents. By taking the ratio of the factors in these two rows, it can be seen that the 100% explosive release case raises the mean loss by 2.21 and the 90th percentile by 2.18, but does not change the maximum. Thus, explosive releases do result in higher losses.

The final three rows of Table 10-3 do not show any unusual sensitivities. As expected, the losses are lower with 1985 CF release quantities. For reasons of conservatism, in all the original runs a high transfer function was assumed. With lower transfer functions, lower loss distributions were observed.

One of the greatest areas of uncertainty appears to be in the estimation of mean failure exposure values. Since numbers of failures are computed outside the simulation, this variable was not included in the sensitivity runs. However, by examination of individual cases, one can show that dosages in most of the high loss cases are insufficient to cause damages to all households in the path of the clouds. In other words, according to our assumptions about vulnerability, the conditional risk profiles do not show substantial widespread economic losses. If these mean failure values are lowered substantially, the losses will greatly increase.

In Chapter 11, some additional discussion is given concerning the sensitivity of the national risk profile with respect to the model assumptions.

TABLE 10-3

SENSITIVITY ANALYSES OF CONDITIONAL PROFILES
(Based on 1993 Profiles)

CASE	CHANGE* IN MEAN	CHANGE* IN 90TH PERCENTILE	CHANGE* IN MAXIMUM
Higher Carbon Fibers and Shorter Burn Times (Boston)			
Burn Time = 4 min.			
CF Released (kg.) 318 - small			
for Total Destruction 454 - medium	4.48	4.95	2.88
1384 - large			
20% of above values for Substantial Damage			
All Explosive			
Large Plane			
Take-off	3.58	3.71	1
Total Destruction (Los Angeles)			
All Large Plane			
Take-off			
Total Destruction	1.62	1.70	1
(Average of Los Angeles and Newark)			
Minimum Transfer Rate (Los Angeles)	.21	.16	.24
Median Transfer Rate (Los Angeles)	.70	.64	.74
1985 CF Amounts (Los Angeles)	.37	.35	.30

* Changes are expressed as the ratio of the new total loss value to the old value. Each run was based on 300 iterations for the indicated cities.

10.5 REFERENCES

1. U.S. D.O.T., F.A.A., Information and Statistics Division, Washington, D.C.
2. F.A.A. Air Traffic Activity, Fiscal Year 1977 , F.A.A.
3. F.A.A. Statistical Handbook of Aviation, Calendar Year 1976 , F.A.A.
4. Personal Communication, David Hoaglin, Harvard University.

11. SYNTHESIS OF NATIONAL RISK PROFILE

11.1 INTRODUCTION

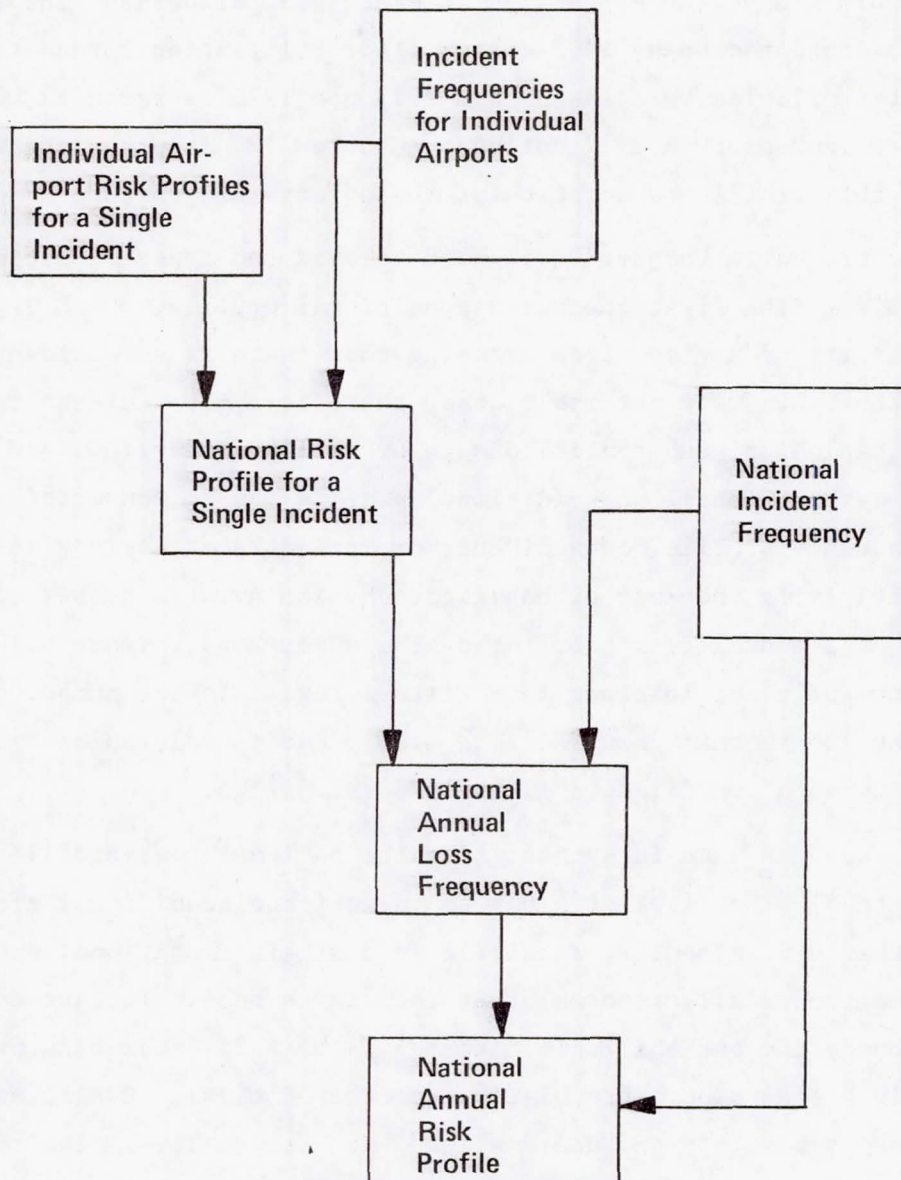
This chapter presents the methodology used and results obtained in computing the national risk profile. The computation was performed by use of the twenty-six individual conditional risk profiles, together with the extrapolation of these profiles to other U.S. airports. The risk profile was obtained using 1993 carbon fiber utilization forecasts, but numbers of facilities were taken from 1972 and 1975 census data, while losses were expressed in 1977 dollars. Chapter 12 discusses the interpretation of this profile to account for the effects of growth.

As mentioned in Chapter 10.1, we developed two types of national risk profiles. The first one was a conditional profile, which expressed the probability of a given loss assuming that there is an accident somewhere in the U.S. (more precisely, that there is a jet accident involving a fire or explosion, substantial damage or total destruction, and a craft utilizing carbon fiber). A conditional profile can be converted into an annual frequency profile for accidents or incidents of a given loss by simply multiplying the loss probabilities by the average number of accidents per year. The annual risk profile, on the other hand, presents the distribution of total loss per year without regard to the number of accidents or incidents that incurred this loss. Additional explanation of these two types of profiles is given in Section 11.5.

The procedure used in synthesizing the national risk profile consisted of three steps: The first step was to investigate conditional risk profiles for the other U.S. airports, resulting in a single conditional profile for the combination of all airports other than large hubs. The second step was to compute the probabilistic mixture of the individual risk profiles (twenty-six cities plus extrapolation to other cities). Cruise accidents were treated separately and are discussed in Section 11.4. The final step was to take the conditional national profile, compute the expected number of accidents nationally per year, and produce the national risk profile. These steps are depicted in the flowchart in Figure 11-1.

FIGURE 11-1

DERIVATION OF NATIONAL RISK PROFILE



In utilizing a Monte Carlo simulation procedure of this type, the sensitivities must be carefully analyzed. A risk profile must be as accurate as possible in estimating probabilities of very high loss events in the tail of the distribution. We, therefore, attempted to develop statistical confidence bounds for the risk profile. The sensitivity of the solution with respect to some of the assumptions will also be discussed.

11.2 EXTRAPOLATION FOR OTHER AIRPORTS

The extrapolation procedure for airports other than large hubs proceeded as follows. We first looked at correlations between city characteristics and parameters of the conditional distribution. The number of establishments per city explained less than 15% of the variance in the parameters of the twenty-six conditional risk distributions. Since large hubs account for 68% of passenger enplanements and about 59% of air carrier departures, we made the alternative assumption that the conditional risk distribution for the medium and small hubs is identical to the average large hub distribution. The approach is conservative since larger hubs tend to show a higher conditional risk. Hence, we used the twenty-six city synthesis as a basis for the national distribution.

11.3 DEVELOPMENT OF A CONDITIONAL NATIONAL RISK PROFILE

The second step in the synthesis of a national profile was to develop a conditional distribution for loss given an accident anywhere in the nation. That is, if there is an accident somewhere in the U.S. involving a jet aircraft using carbon fibers and resulting in a fire or explosion, the distribution of losses is given by this conditional profile. The profile is obtained by a simple probabilistic mixture of the twenty-six individual conditional risk profiles. That is,

$$F(X) = P_1 F_1(X) + P_2 F_2(X) + \dots + P_{26} F_{26}(X)$$

where:

$F(X)$ = probability that total loss is greater than or equal to X
given an accident in the U.S.

$F_i(X)$ = probability that loss is greater than or equal to X given an accident at airport i (where we assume that the accident takes place at one of the 26.)

P_i = conditional probability that an accident occurs at airport i given that it occurred in the U.S.

To compute the conditional national risk profile we computed $F(X)$ from the above equation for several dollar values. This computation involved two technical tasks before the equation could be evaluated. These were:

- computation of the $F_i(X)$ for given values of X ,
- computation of P_i

The twenty-six individual risk profiles (see Table 10-1) were expressed in terms of fixed percentiles rather than in the fixed dollar values required by the above equation. To determine the $F_i(X)$ for fixed dollar values, we performed a logarithmic linear interpolation of the points for the individual risk profiles (that is, a straight line was connected between the fixed percentile data on a logarithmic basis). Log-linear interpolation was preferred to linear interpolation because of the concave nature of the risk profile. Maximum dollar value for each city represented an expected percentile of 300/301. We terminated the $F_i(X)$ at a value of \$9.02 million (this was the maximum loss calculated in the twenty-six original simulations; it was observed for Los Angeles). To extrapolate to \$9 million the twenty-five risk profiles for which \$9.02 million was not an observed data point, a log-linear relationship was again utilized. We determined P_i as follows:

$P_i = \text{Pr} (\text{accident occurs at airport } i \text{ on the next operation anywhere in U.S.} \mid \text{accident occurs on next operation anywhere in U.S.})$

$= \text{Pr} (\text{accident occurs on next operation anywhere in U.S.} \mid \text{accident occurs at airport } i \text{ on next operation anywhere in U.S.}) \times \text{Pr} (\text{accident occurs at airport } i \text{ on next operation anywhere in U.S.}) \div \text{Pr} (\text{accident occurs on the next operation anywhere})$

$$= 1 \times \text{Pr (next operation anywhere in U.S. occurs at airport } i) \times (P(\text{ACC}_i) \div P(\text{ACC}))$$

$$= \frac{\text{annual number of operations at airport } i}{\text{total annual operations in U.S.}} \times (\text{weather factor})$$

where $P(\text{ACC}_i)/P(\text{ACC}) = \text{weather factor} = 4.52 \times \text{Prob}(\text{IFR}_i) + .58 \times \text{Prob}(\text{VFR}_i)$

As discussed in Chapter 4, the weather factor accounts for the fact that accidents are more likely in IFR weather. To estimate the number of operations at each airport we multiplied U.S. departures by 2 and then by a foreign adjustment factor. The foreign adjustment factors were estimated using an international flight schedules book [1]. These factors were highest for New York and Miami, but were 10% or under for all other airports. The weather factors were computed IFR statistics for a number of airports. There were a few airports for which we did not have these data, in which case the IFR probability was estimated. The factors utilized in the equation for P_i are presented in Appendix C.

The national conditional risk profile computed by the above procedure is shown in Table 11-1. The mean value, or expected loss per incident was \$131,000, but there was a large variation in losses; the standard deviation was \$417,000. While 51% of all accidents exceed \$10,000 loss, only 2% exceed \$1 million in loss.

11.4 COMPUTATION OF ANNUAL EXPECTED NUMBER OF ACCIDENTS

To complete the national risk profile we needed to determine the expected number of accidents involving fire or explosion, substantial damage or total destruction, and jet aircraft utilizing carbon fibers.

To perform this computation we made an adjustment to account for cruise accidents. Based on our accident probability model, the frequency per jet operation for non-cruise accidents is 5.23×10^{-7} per operation. The accident rate for cruise accidents is 1×10^{-7} per operation. Based on the fact that standard metropolitan statistical areas occupy 1/12 of the nation's area [2], we concluded that the probability of a cruise accident occurring over a metropolitan area is 1/12 times

TABLE 11-1

NATIONAL CONDITIONAL RISK PROFILE - 1993

LOSSES X	CUMULATIVE PROBABILITY OF LOSSES LESS THAN X	PROBABILITY OF LOSSES GREATER THAN X	ANNUAL FREQUENCY OF INCIDENTS* WITH LOSSES GREATER THAN X
100	.180	.820	2.6
1,000	.298	.702	2.2
10,000	.488	.512	1.6
100,000	.727	.273	.87
500,000	.946	.054	.17
1 million	.978	.022	.07
2 million	.9922	7.8×10^{-3}	.025
5 million	.9983	1.7×10^{-3}	5×10^{-3}
9.019 million	.99937	6.3×10^{-4}	2×10^{-3}
10,000,000	.99946	5.4×10^{-4}	1.7×10^{-3}

Median: 11,200

Mean: 130,920

Standard deviation: 416,835

*Based on frequency of 3.2 jet accidents per year involving CF composites and fire.

10^{-7} per operation or 8.3×10^{-9} per operation. This probability is low compared to the probability of a non-cruise operation and we therefore did not run any special simulations for a cruise type accident. However, we did note that the probability of a cruise or non-cruise accident occurring over a metropolitan area is 5.3×10^{-7} per operation (this is simply the addition of the two probabilities for accidents occurring over metropolitan areas) and we utilized this adjusted number in subsequent calculations.

Given the probability of an accident over a metropolitan area, we then computed the expected number of accidents in 1985 and 1993. This expected number was for accidents meeting the following criteria.

- jet operation
- jet utilizing carbon fibers
- accident characterized by fire or explosion
- accident occurs in a metropolitan area
- accident involves total destruction or substantial damage

The appropriate expected value is determined from the following expressions.

$$\left(\begin{array}{l} \text{Expected Number of} \\ \text{Accidents per Year} \\ \text{as Derived from} \\ \text{the Base Period} \end{array} \right) \times \left(\begin{array}{l} \text{Percentage of} \\ \text{Operations} \\ \text{Involving Aircraft} \\ \text{Utilizing Carbon} \\ \text{Fibers} \end{array} \right) \times \left(\begin{array}{l} \text{Adjustment} \\ \text{for Projec-} \\ \text{tion Year} \end{array} \right) \times \left(\begin{array}{l} \text{Adjustment} \\ \text{for Foreign} \\ \text{Air Carrier} \\ \text{Operations} \end{array} \right)$$

As derived from the base period, the expected number of accidents per year is:

$$\begin{aligned} & 5.3 \times 10^{-7} \frac{\text{accidents}}{\text{operation}} \times 65.2 \text{ million jet operations} \div 9 \text{ years} \\ & = 3.83 \text{ accidents/year} \end{aligned}$$

From NASA projections, the overall percentage of aircraft utilizing carbon fibers will be 55% in 1993 (50% for small jets, 60% for medium jets, and 50% for large jets).

To determine the adjustment for 1993, we utilized the NASA projection of 3800 total aircraft in 1993 compared to 2600 today. Although there has been a slight increase in jet operations and fleet size between the start

of the base period in 1968 and today, any increase in operations must be balanced against improved safety records. The number of accidents per year has actually decreased slightly. Table 11-2 presents some U.S. jet accident statistics by year. In view of possible safety improvements by 1993, the ratio 3800/2600 can be deemed conservative.

We estimated the adjustment for foreign operation to be 1.04, to account for the fact that the 65.2 million jet operations do not include foreign operations. Combining all of these factors the expected number of accidents of interest in 1993 is:

$$3.83 \times \frac{3800}{2600} \times .55 \times 1.04 = 3.2$$

The appropriate factor for 1985 is discussed in Section 11.8.

11.5 CONVOLUTION PROCEDURE FOR NATIONAL PROFILE

In this section we present the two types of national risk profile that were developed. To produce a loss profile for the frequency of events resulting in losses of a given amount, the conditional profile was simply multiplied by 3.2 as shown in Table 11-2. The resulting profile is presented in Figure 11-2. This loss frequency profile may be interpreted as follows: Suppose that we wish to know how often we might expect an accident which results in losses of \$1 million or more. According to Table 11-1, the probability of such an accident is 0.02. By consulting Figure 11-2, we find that the expected number of such accidents during one year is about 1/10 (more precisely, it is 0.07). Hence an accident incurring over \$1 million in damage would occur about once every ten years (more precisely, once every 14 years). In the next chapter, this profile will be compared against other risks due to natural or man-made causes.

To develop a profile based on total loss without regard to the number of accidents, the following formula was utilized:

$$F(X) = P(0) + P(1) F^{(1)}(X) + P(2) F^{(2)}(X) + \dots$$

where:

$P(i)$ = probability that Poisson variate with parameter
3.2 is equal to i .

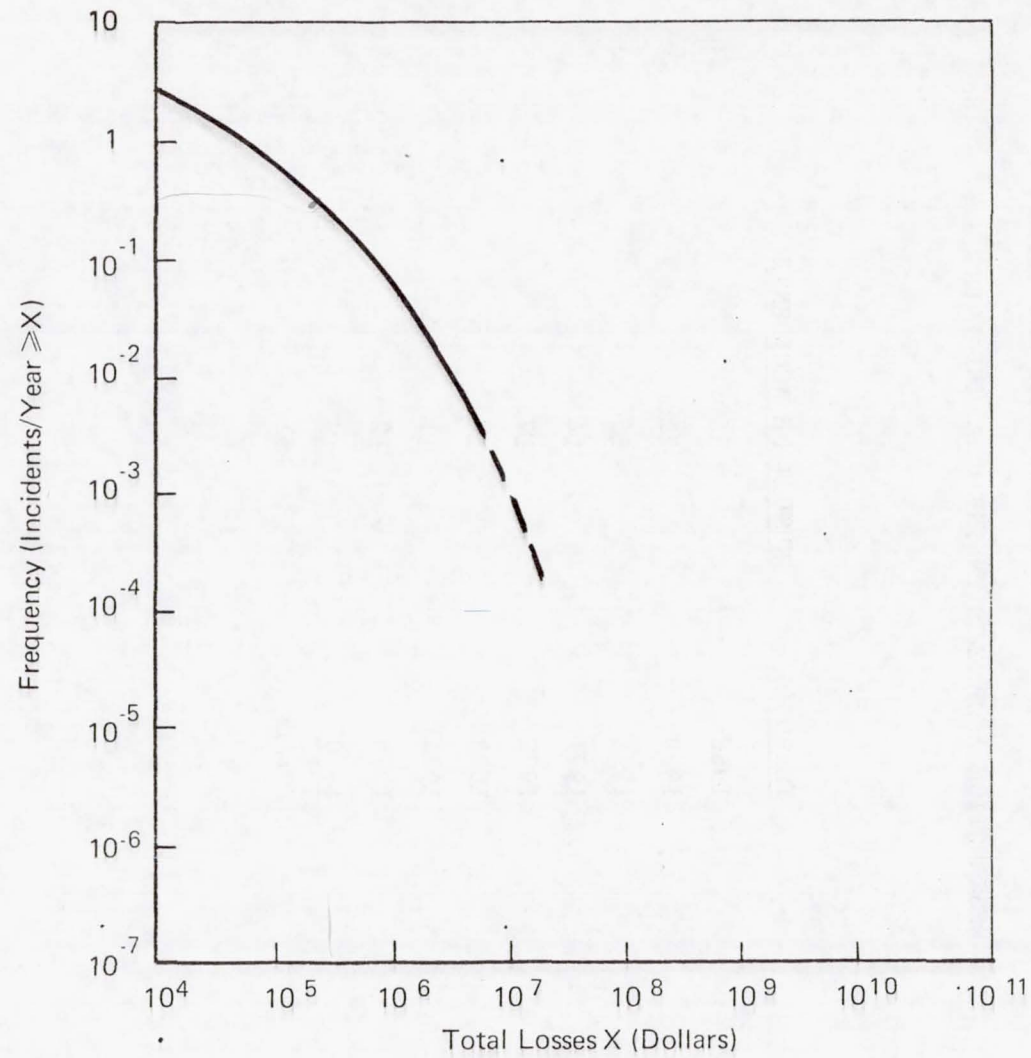
TABLE 11-2

HISTORY OF SUBSTANTIAL DAMAGE AND TOTAL
DESTRUCTION ACCIDENTS IN THE U.S. INVOLVING U.S. JETS

<u>YEARS</u>	<u>NUMBER OF ACCIDENTS</u>
1968	16
1969	21
1970	15
1971	14
1972	17
1973	16
1974	11
1975	12
<u>1976</u>	<u>9</u>
TOTAL	131

FIGURE 11-2

National Loss Frequency with 1993 CF Utilization
(Annual Frequency of Losses of Various Magnitudes)



$F^{(i)}(X)$ = probability that loss is less than or equal to X
given i accidents.

$F(X)$ = probability that total annual loss is less than X.

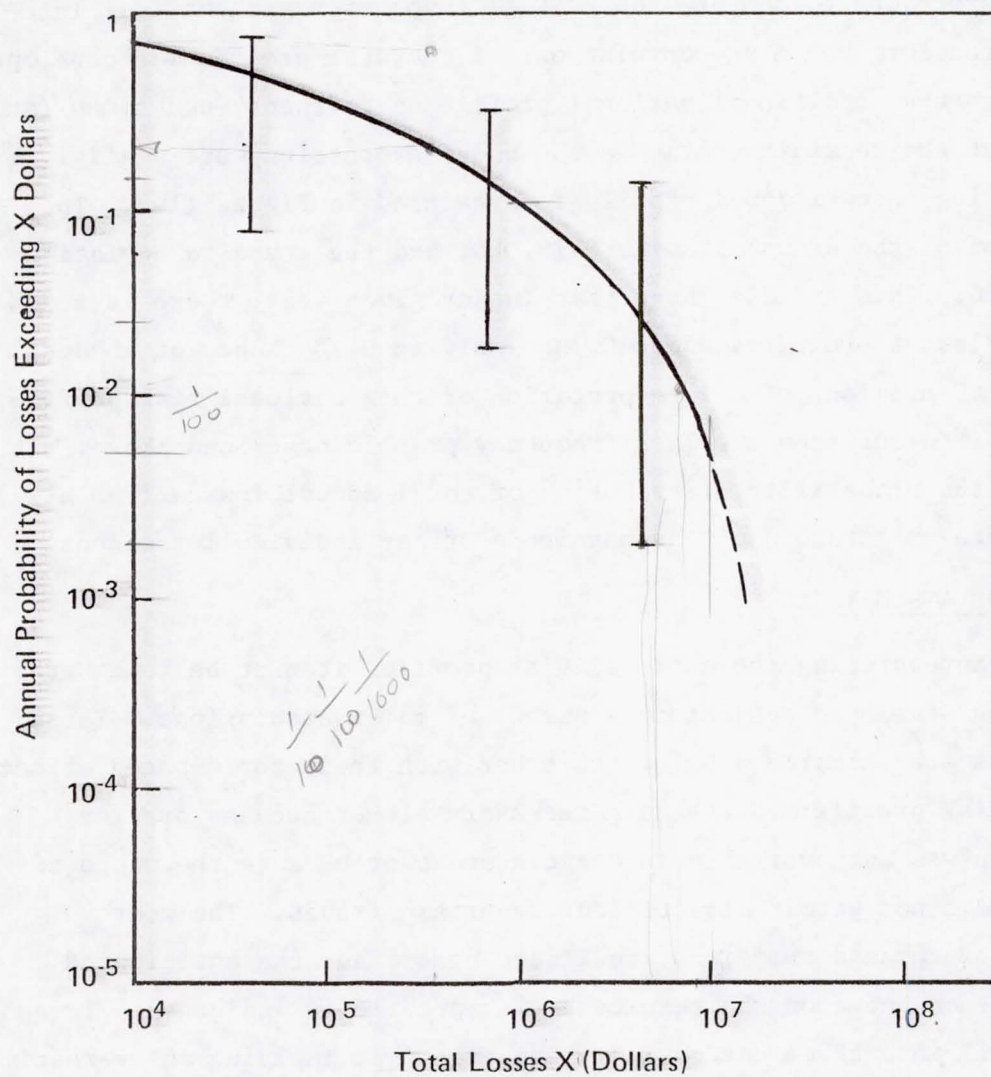
The procedure to compute the $F^{(i)}(X)$ involves a mathematical integration procedure known as convolution. A computer program was developed to convolve the conditional national profile up to twenty-one times (at which point the remaining terms in the above expression were negligible). The resulting unconditional profile is presented in Figure 11-3. The expectation of the annual loss is \$419,000, and the standard deviation is \$785,000. This profile shows that in any given year, there is a 72% chance of losses exceeding \$50,000, but only an 0.7% chance of losses exceeding \$9 million. The interpretation of this national risk profile is quite different from the loss frequency profile described above. It expresses the probability distribution of total annual losses from all CF accidents, regardless of the magnitude of any individual accident.

11.6 MAJOR ASSUMPTIONS

When interpreting the national risk profile, it must be remembered that it was developed subject to a number of major assumptions. These assumptions are summarized below, together with their anticipated effect upon the risk profile: These were necessary either because precise information was not available in certain areas, or because the scope of the study did not permit elaboration of certain issues. The most important of these assumptions are listed below, and the anticipated effect of each one upon the resultant risk profile is indicated. These effects fall into three categories: conservative, implying an overestimation of risk; non-conservative, implying an underestimation of risk; and unclear, implying that no definite effect upon the risk can be expected in either direction. Most of the assumptions that were adopted are conservative, but particularly in the area of economic loss estimation there may be additional costs which we were not able to quantify. Future investigations will focus upon validating or modifying some of these assumptions, and obtaining more detailed descriptions of economic impacts upon various facilities.

FIGURE 11-3

NATIONAL ANNUAL RISK PROFILE FOR
CARBON FIBER RELEASES FROM COMMERCIAL AIR CARRIERS
(1993 CF Utilization)



EXPECTED ANNUAL LOSS = \$419,000
STANDARD DEVIATION = \$785,000

- If an aircraft carries composite, and a fire occurs, the composite will always be involved.
Effect: Conservative. Portions of the aircraft containing CF may not be damaged by fire.
- Explosive releases of CF are possible, in which up to 25% of the CF mass can be released almost instantaneously.
Effect: Conservative. It has not yet been demonstrated that fuel deflagrations in aircraft fires will produce this phenomenon.
- All CF released from a fire is in the form of single fibers.
Effect: Conservative. Single fibers will disperse farthest, and have the greatest potential for penetrating to equipment. (The one possible exception is the vulnerability of power stations to clumps of fibers.)
- Atmospheric conditions remain constant during dispersion of the carbon fiber cloud.
Effect: Unclear. Though weather will fluctuate, the net effect on dispersion should average out over many simulation trials.
- The presence of precipitation is ignored in the dispersion analysis.
Effect: Conservative. Precipitation would tend to wash out airborne fibers and reduce downwind exposures.
- Within a facility category, all facilities are assumed to be similar in terms of penetration properties and economic characteristics.
Effect: Unclear. Considerable variations will exist among facilities, but these will average out when losses are aggregated over a large area.
- Equipment is assumed to be in an activated state during exposure.
Effect: Conservative. Reactivation of equipment after exposure may produce failures, but vulnerability in such a case is most probably reduced.

- Penetration transfer functions were set at the maximum of their range for each facility category.
Effect: Conservative. (See sensitivity analysis in Chapter 10).
- If a unit of critical equipment fails, the facility is shut down.
Effect: Conservative. The presence of redundancies or backup equipment may minimize economic loss.
- Secondary impacts of business interruption are not included in the economic loss estimate.
Effect: Non-conservative. The shutdown of one facility may have subsequent impact upon other sectors of business or society at large (e.g., mass transit, telephone system).
- The amount of vulnerable electronic equipment is assumed to remain at current levels.
Effect: Non-conservative. Rapid growth is expected in the electronics industry during the next decade. (See Chapter 12).
- Costs associated with decontamination and precautionary procedures are not incorporated.
Effect: Non-conservative. The cost of anticipating failures due to CF release or of preventing additional failures subsequent to a release may be significant, especially at vital installations such as airports.

Additional assumptions of lesser importance were made in the course of the analysis, and these are detailed in each of the preceding Chapters 3 to 9.

11.7 SENSITIVITY ANALYSES AND CONFIDENCE BOUNDS

One of the more important issues concerning the two risk profiles is their statistical accuracy. For example, what is the true probability of obtaining a loss in excess of nine million dollars? To answer such questions we derived confidence bounds and identified sources of error in the profile.

The possible sources of error in generating the risk profile consist of:

- Errors in assumptions and values of constants.
- Possible variability in parameters.
- Statistical errors in the estimates of sample parameters.
- Statistical accuracy of conditional profiles.

If we assume that the modelling assumptions and parameters are accurate, then:

- The conditional risk profiles are true samples from the appropriate sampling distribution
- The conditional national profile is a true stratified sample
- The convolution procedure is an accurate method of obtaining a risk profile from the conditional national risk profile.

Any errors in the various stages of the analysis will therefore impact one or both of the two risk profiles. The four possible sources of errors are discussed in this section.

Regarding the first possible source of error, the various assumptions of the model have been documented above. For some of these assumptions, such as constant atmospheric conditions, the impacts are unclear. Other assumptions concerning values of constants are difficult to verify, such as average exposure for equipment failure, or percentage of carbon fibers released in a fire. Confidence bounds for these assumptions will necessarily be judgmental. However, for some of the constants, the sensitivity analysis gives an indication of the relative impact of our assumptions.

As an example, losses were moderately sensitive to amounts of fibers released.

The second possible source of error was the probabilistic variability of values assumed to be constant. Such variability can increase the variance of the risk profile. An example is the impact of the possible variability in the mass of carbon fibers used on aircraft. The original assumptions on CF use were agreed upon by A.D.L., NASA, and representatives of the air-framers. One possible area of future refinement would be to implement a distribution for CF involved in an accident. For the time being, bounds on the risk profile can be estimated by a sensitivity run with the maximum possible CF amounts; this was performed in Chapter 10.

We also considered the possible variability of economic loss factors, and concluded that such variability does not have a great impact on the risk profile. This is demonstrated in Appendix H. In general, the variability of conditions at exposed facilities will not greatly alter the risk profile. However, the variability of carbon fiber release conditions may be a source of additional uncertainty, and merits further investigation.

The third and fourth sources of possible error are amenable to a more rigorous statistical determination of confidence. The confidence bounds developed below are due only to statistical estimation and do not reflect any modelling errors.

Among the simulation inputs, there are several parameters based on statistical estimates. Some of these are based on a large body of statistical data, for example, the number of operations used to estimate the values of P_i in section 11.3, and the weather statistics used in developing the individual airport profiles. Because these represent large numbers of airport operations and weather observations, there is very little error in the estimates (assuming the correctness of the model for P_i).

A different situation exists with the estimated expected value of 3.2 accidents per year, used in the convolution procedure. This estimate is based on the Poisson sample of accidents during the base period, and is subject to statistical fluctuation. Again, assuming that the procedure in determining the estimate is valid (we believe that it is actually

conservative) a statistical confidence bound can be developed as follows:

The major statistics used in determining the 3.2 expected accidents per year in 1993 include the 81 total fire and explosion accidents. We also utilized the fraction of total accidents involving U.S. jets, but this statistic has a lower percentage variance and thus, the variance of the estimate is dominated by the variance of the statistic of 81 accidents. We can thus develop a confidence bound for the 3.2 estimate based on confidence bounds for the statistic of 81 accidents. From Chapter 4, this confidence interval is 65 to 101.

When this confidence interval is utilized in the estimate of 1993 accidents, we obtain a range of estimates from 2.6 to 4.0.

When 2.6 and 4 accidents are utilized in the convolution procedure, we obtain the confidence intervals depicted in Table 11-3. This interval reflects the major source of possible errors in statistical estimation of parameters.

The final source of uncertainty is in the statistics of simulation, and the accuracy of the empirically generated national conditional profile. To investigate the likelihood of losses exceeding the highest observed value of \$9 million, we performed an extended simulation involving 1,500 iterations for the Los Angeles case. There were no losses, however, in excess of the \$9 million dollars.

A statistical method was developed for deriving confidence bounds for the national conditional profile. The method is explained in Appendix H.2. Bounds obtained in this manner for the conditional national profile are presented in Table 11-4.

Examining these two statistical approaches to sources of error, we find that each source of uncertainty adds less than a 5% increase at the high end of the distribution (lower dollar values) and no more than a doubling at the extreme low end of the distribution (high dollar values). Based on these statistical uncertainties, and in consideration of the modelling assumptions, we estimate that a confidence bound accounting for all factors would increase the probability of the high cost events by no more than one decade, and would increase the probability of the

TABLE 11-3

NINETY-FIVE PERCENT CONFIDENCE BOUNDS OF THE NATIONAL ANNUAL PROFILE
UTILIZING POISSON CONFIDENCE BOUNDS OF 2.6 AND 4.0 ACCIDENTS PER YEAR
AND NO OTHER UNCERTAINTY

<u>Dollar Value</u>	<u>Lower Confidence Bound of Probability of Loss Exceeding Value</u>	<u>Upper Confidence Bound of Probability of Dollar Loss Exceeding Value</u>
500	.845	.951
5,000	.787	.910
50,000	.635	.799
500,000	.246	.405
2,000,000	.054	.119
9,019,000	5×10^{-3}	1.2×10^{-2}

TABLE 11-4

NINETY PERCENT (5% OF EACH TAIL) CONFIDENCE BOUNDS FOR THE CONDITIONAL
NATIONAL RISK PROFILE DUE TO STATISTICAL EFFOR
IN SIMULATION AND NO OTHER UNCERTAINTY

<u>Dollar Value</u>	<u>Lower Confidence Bound on Probability of Loss Exceeding Value</u>	<u>Upper Confidence Bound on Probability of Loss Exceeding Given Value</u>
100	.807	.833
1,000	.686	.718
10,000	.495	.532
100,000	.257	.289
500,000	.046	.062
1 million	.017	.028
2 million	5.3×10^{-3}	11.5×10^{-3}
5 million	8.5×10^{-4}	4×10^{-3}
9.019 million	2×10^{-5}	1.3×10^{-3}

low cost events by a smaller amount. In view of the extremely small lower confidence bound for \$9.019 million in Table 11-4, and the modelling error, we would equate the lower confidence bound at this value to 0, but stipulate tighter lower bounds at lower dollar values. These bounds are illustrated along with the national profile in Figure 11-3.

11.8 PROJECTIONS BETWEEN 1977 AND 1993

Before 1993 there will be a very limited use of carbon fibers in commercial aircraft. The airframers project that only 20% of small and medium jets and 33% of large jets will be utilizing carbon fibers in 1985. Furthermore, the amount of carbon fibers utilized in these planes will be only 20% of the amounts utilized in 1993. As a result of this, the loss distribution in 1985 will be smaller than the loss distribution in 1993 and will not be of major consequence.

To estimate the profile for 1985, we performed a simulation for the hub showing the highest expected conditional loss in 1993, namely, Los Angeles, using 1985 CF usage forecasts. We then extrapolated the national conditional profile according to the relationship between the 1985 Los Angeles profile and the 1993 Los Angeles profile. The resulting conditional profile is given in Table 11-5.

To perform the extrapolation, we noted the following comparisons between the 1985 profile for Los Angeles and the 1993 profile for Los Angeles:

RATIOS OF 1985 AND 1993 LOS ANGELES PROFILES

<u>Characteristic of Profile</u>	<u>Ratio of 1985 to 1993</u>
mean	.37
50th percentile	.127
75th percentile	.119
90th percentile	.35
maximum	.30

We then constructed the distribution in Table 11-5 so that the comparison of the 1985 and 1993 conditional national profiles closely resembled the comparisons above. The dollar values through the fiftieth

TABLE 11-3

NATIONAL CONDITIONAL RISK PROFILE - 1985

<u>AMOUNT X</u>	<u>PROBABILITY LOSS IS LESS THAN X</u>	<u>PROBABILITY LOSS IS GREATER THAN X</u>	<u>EXPECTED FREQUENCY OF INCIDENTS EXCEEDING X</u>
60	.25	.75	.82
1,200	.48	.52	.57
10,000	.64	.36	.40
35,000	.73	.27	.30
175,000	.946	.051	.06
700,000	.9922	.0078	.0085
1,750,000	.9983	.0017	.0019
3,156,790	.99937	6.3×10^{-4}	6.9×10^{-4}

Mean = 46,000

Standard deviation = 146,000

percentiles were multiplied by .12 and dollar values of the 75th percentiles and above were multiplied by .35. (We multiplied the 75th percentile value by .35 rather than .12 to preserve consistency of the mean). The resulting mean values had a ratio of .35.

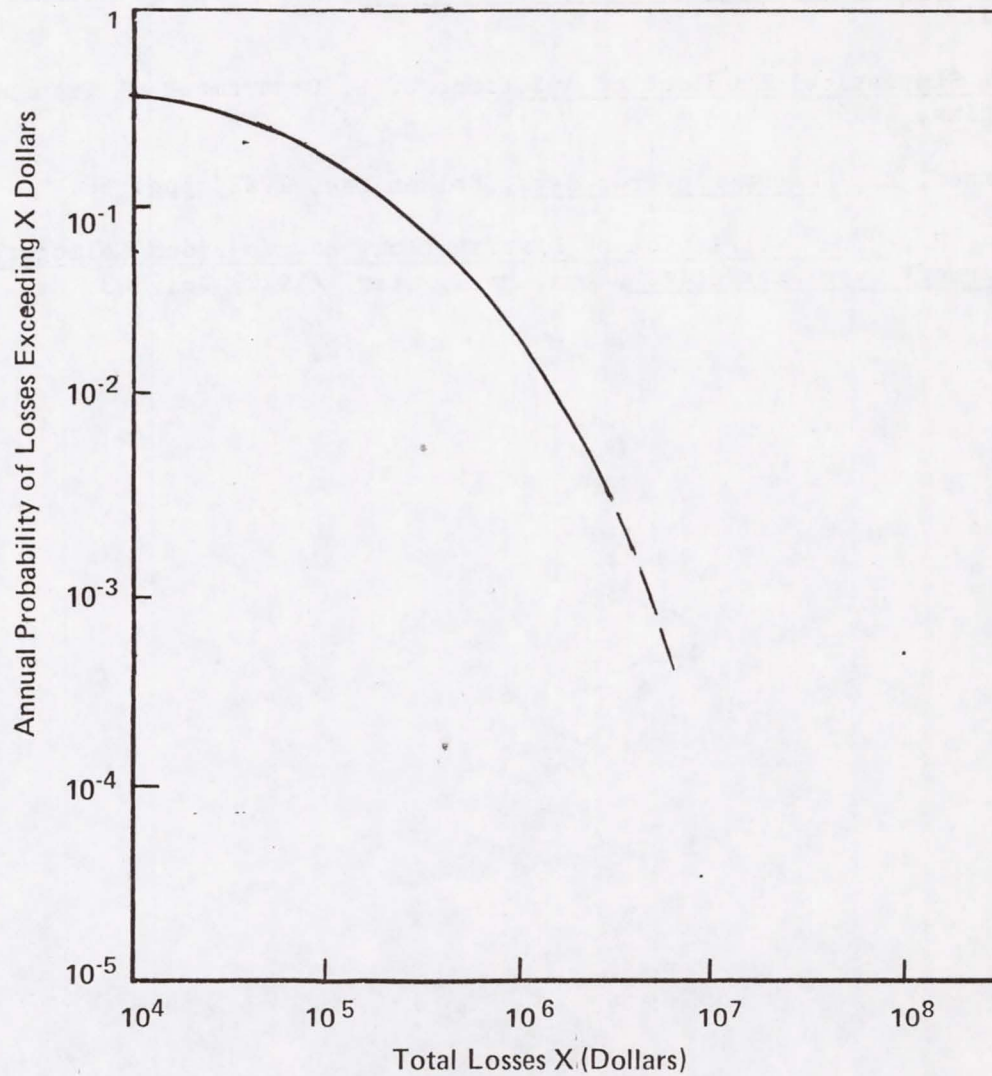
This procedure was not as accurate as the full simulation of 26 cities. However, because of the relatively low carbon fiber usage predicted in 1985, our primary emphasis was on the 1993 profile. It is clear that the 1985 profile represents substantially lower losses than the 1993 profile.

We also noted that the reduced fleet size (3300 versus 3800) for 1985 and the reduced percentage of airplanes utilizing carbon fibers will result in an expected number of relevant accidents per year of 1.1 in 1985. We then convoluted the estimated 1985 distribution with Poisson probabilities corresponding to an expectation of 1.1. The resulting national profile is depicted in Figure 11-4.

In this case, the average loss has decreased to only \$51,000, and the chances of exceeding \$3 million in losses are only one in 1000. When compared with the 1993 risk profile, this curve is more than a decade lower in probability at the high-loss end.

FIGURE 11-4

ANNUAL RISK PROFILE FOR
CARBON FIBER RELEASES FROM COMMERCIAL AIR CARRIERS
(1985 CF Utilization)



EXPECTED ANNUAL LOSSES = \$51,000

STANDARD DEVIATION - \$161,000

11.9 REFERENCES

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12. INTERPRETATION OF RESULTS

12.1 INTRODUCTION

The foregoing chapters have presented an analysis of the risks to the nation which may arise due to carbon fiber releases from air carrier accidents. The purpose of this final chapter is to place these risks in perspective by examining their implications for society as a whole. We will also address some additional aspects of risk estimation which were not dealt with by the simulation modelling approach, and we will indicate open issues which may require further study.

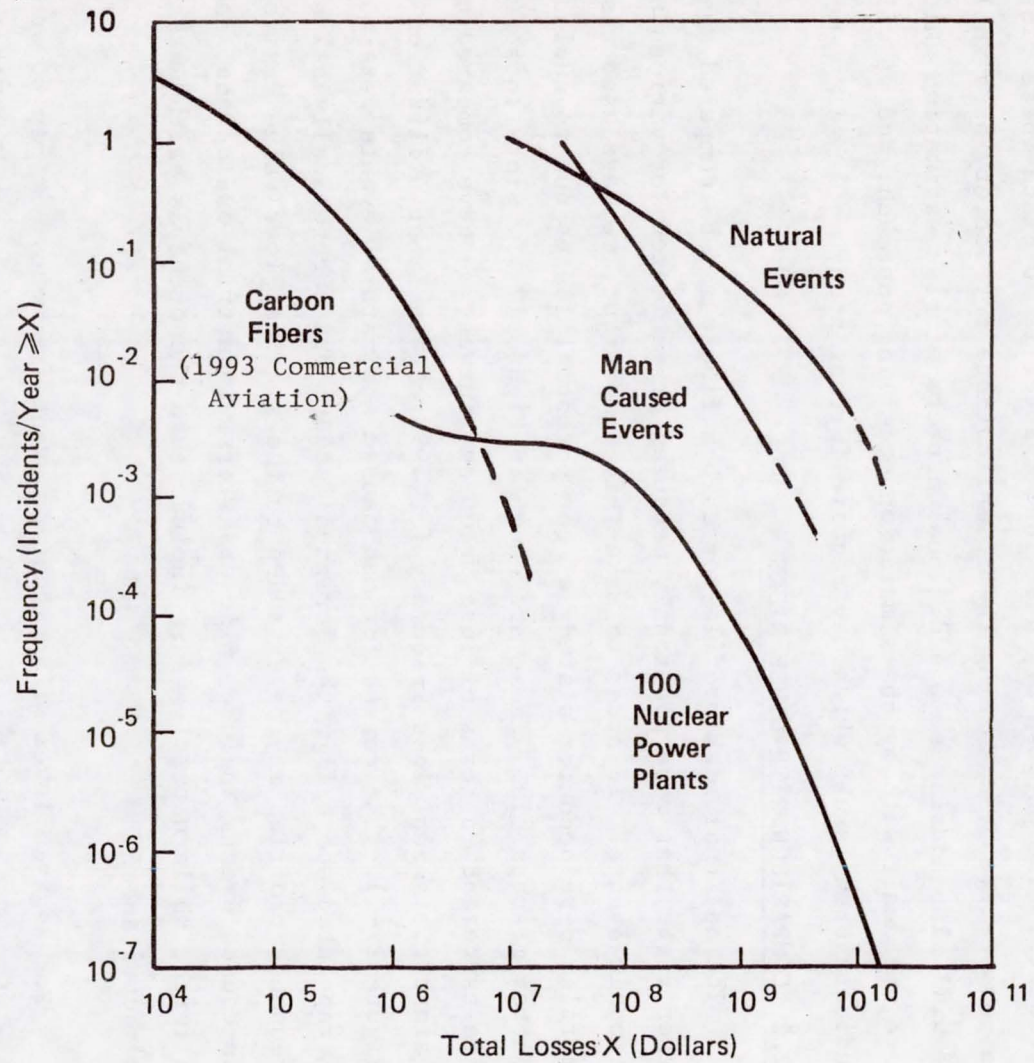
12.2 COMPARISON WITH OTHER RISKS

The national risk profile for carbon fibers may be compared against other risks that were previously measured or estimated for various catastrophic events. In order to make this comparison, we have used risk profiles developed for a study of the potential losses due to nuclear reactor mishaps [1]. These are shown in Figure 12-1. Since these risks were expressed in terms of loss frequency curves, we have compared them against the annual loss frequency for 1993 carbon fiber utilization (Figure 11-2). The curves for man-caused and natural events were not extrapolated above 1 in the original study, but theoretically all such frequency profiles may be extended to the smallest loss value desired. Man-caused events include mine disasters, industrial explosions, and so forth, while natural events include such phenomena as earthquakes and hurricanes.

For a given level of accident or event frequency, it may be seen that the anticipated losses due to carbon fibers are considerably lower than the losses from these other events. For example, with a frequency of one in a hundred, carbon fiber losses will exceed approximately two million dollars. (In other words, there is a 1% chance that in 1993 an aircraft accident will result in two million or more of economic losses.) In the case of man-caused events, the losses at a frequency of 1/100 per year would be in excess of a billion dollars, while for natural events they would exceed ten billion dollars. Hence there is a difference of three or four orders of magnitude in economic loss. The nuclear reactor accidents

FIGURE 12-1

COMPARISON OF FREQUENCIES OF LOSS



occurring within a population of 100 nuclear plants appear to be lower in frequency, but are also estimated to cause higher losses than carbon fibers. For example at a frequency of one in a thousand, carbon fiber losses would exceed ten million dollars, whereas nuclear accident losses would exceed 100 million dollars. The nuclear plant risk profile has been extended down to extremely low probabilities, with corresponding losses on the order of billions of dollars. However, as discussed in Section 11.7, it is highly unlikely that a single carbon fiber accident could ever exceed the fifty million dollar level, according to our extrapolation.

In order to evaluate the risk from carbon fibers, one must also consider the benefits that they provide, as is pointed out in the stakeholder analysis below. We are frequently exposed to other risks from which we derive no benefits, such as naturally-caused catastrophes. In addition, one must recognize that we expose ourselves to certain risks voluntarily, while other risks are "involuntary" in the sense that they are imposed upon us by forces over which we have no control. An example of voluntary risk is mountain-climbing or driving an automobile, while involuntary risks include natural disasters and infectious diseases. Generally speaking, people are willing to tolerate a much higher level of voluntary risk than involuntary risk, presumably because they choose to take the risk in order to gain some tangible or intangible benefit. In the case of carbon fiber releases, the risk imposed upon society by the use of CF composites is an involuntary one, since those who suffer the economic impact have not knowingly accepted this risk, nor do they necessarily derive a direct benefit from the presence of carbon fibers on aircraft. In comparing risks, it is important to make these distinctions, so that voluntary risks are distinguished from involuntary risks. The risk profiles in Figure 12-1 all represent involuntary risks.

12.3 POTENTIAL SHOCK HAZARDS

The possibility exists that people may experience electrical shocks due to contact with electrical equipment in which carbon fibers have

created a short circuit or low impedance path. As mentioned in Chapter 8, this possibility has not been fully explored, and existing knowledge is insufficient to quantify the likelihood of such an event. For this reason, we did not attempt to construct a risk profile for shock hazards. Even if a shock were experienced, the shock would not necessarily be lethal unless the person involved was grounded, and the conditions under which this is possible are not yet evident. Nevertheless, as shown below, one investigator [2] has attempted to obtain a rough estimate of the national impact of shock hazards, based upon some preliminary experimental results with toasters.

A simple relationship appears to exist between the area covered by an exposure contour and the carbon fiber mass released which gave rise to that contour:

$$E \cdot A = N/V_s$$

where A = total area covered by carbon fiber exposure (M^2)

E = average exposure over area A (FS/M^3)

N = number of fibers released

V_s = settling velocity of fibers

This relationship has been validated with respect to dosages computed by more sophisticated physical dispersion models.

Assuming a mass of 1000 kg. of carbon fibers involved in an accident, of which 20% are released, and assuming 2×10^9 fibers per kg., we obtain figure of 4×10^{11} fibers released. With an accident rate of 3 per year, this amounts to a total of about 1.2×10^{12} fibers released annually. Using a settling velocity of 2 cm./sec., or 0.02 m./sec., we have the following estimate for total area-exposure:

$$E \cdot A \approx 6 \times 10^{13}$$

Now, assuming that shock hazard probability follows an exponential distribution (see Chapter 8), we can use a linear approximation for the low-dosage region of the cumulative distribution function:

$$P_r (\text{hazard at } E) \approx \frac{E}{\bar{E}}$$

where $\bar{E}$ = mean exposure for hazard. If we assume 1000 people per km², of which 1/3 have toasters, this yields 330 toasters/km.², or 3.3×10^{-4} per m.². Hence, the expected number of shock hazards annually is given by

$$\left(\frac{TF \cdot E \cdot A}{\bar{E}} \right) (3.3 \times 10^{-4}) \approx \frac{2 \times 10^{10}}{\bar{E}} (TF)$$

where TF is the transfer function relating external to internal exposure. In experimental exposures to carbon fibers, two toasters were found to fail at 10^5 and 10^8 FS/M³ respectively. Using the lower figure of $\bar{E} = 10^5$, and assuming a conservative transfer function of 0.1 for the typical residence, we find that the expected number of potential shock hazards is 20,000 annually. If the 10^8 failure level were used, the figure would be 20 shock hazards.

The above estimates are difficult to interpret without knowing the probability of a person touching a toaster which was defective, while simultaneously having the correct resistance to ground to permit a lethal shock. Furthermore, it is not known to what extent the population of all toasters is susceptible to this hazard. Consequently, the issue of shock hazard merits further study.

12.4 FUTURE SCENARIOS

The risk analysis described in Chapters 10 and 11 was based upon several different sources of data, which did not necessarily reflect the situation that would exist in 1985 and 1993. The census data were drawn from 1972 for households, and from 1975 for businesses. Moreover, the extent of electronic equipment usage was based upon present-day experience and field surveys, while air traffic characteristics were based upon current technology. Most of these factors will have changed significantly by 1993, and it is worthwhile investigating the effect that probable future scenarios would have upon our risk estimates.

12.4.1 Airport and Aircraft Safety

The probabilistic analysis of aircraft accidents presented in Chapter 4 used a history of accidents to project accident rates into the future. It is conceivable that changes in airport instrumentation, such as the improved landing systems which are currently being introduced, could reduce the incidence of air carrier accidents. However, our analysis of airport safety characteristics showed no meaningful correlation between airport features and accident rates for the existing large hubs. Thus, modernization of airport facilities is not expected to have a substantial effect upon the overall national accident probabilities, although local accident rates may change. On the other hand, airport fire-fighting techniques and aircraft design may have a significant influence on carbon fiber releases, as described in Section 12.6 below.

12.4.2 Population and Industry Growth

Based upon the U.S. population growth trends since 1972, the total population may be expected to grow from its current level of about 210 million to 222 million in 1985 and 236 million in 1993. Much of this growth will probably occur in metropolitan areas, so that the total number of households in the vicinity of airports will increase. However, the percentage increase is small relative to the uncertainty bounds in the risk profile, so that the net effect on our risk estimate would be insignificant. The same is true of industrial growth if we consider merely the numbers of facilities. The factor that could alter the risk profile considerably is building penetration, but our field survey comparisons did not reveal any strong differences between modern and old cities.

12.4.3 Electronic Equipment

The key element of this risk analysis study was the electronic equipment which is subject to failure. However, the electronics industry is undergoing dramatic transformations, and it is difficult to predict an accurate scenario for 1985, let alone 1993. There is a strong trend toward miniaturization and use of integrated circuits, which suggests that

a larger proportion of equipment will be vulnerable to carbon fibers. Electronics applications are expected to proliferate both in home and industry, and minicomputers will become increasingly commonplace. Current projections from ADL industry experts indicate that U.S. semiconductor production will rise from \$1669 million in 1975 to approximately \$4 billion in 1980 and as much as \$6 billion by 1985. (These figures are expressed in 1975 dollars.) Hence, if equipment vulnerability characteristics remain the same, we might expect the dollar losses in our risk profiles to increase considerably by 1993. We must infer that the character of the electronics industry in 1993 remains an important open issue, and that the risk analysis may be non-conservative in this respect.

12. 5 STAKEHOLDER ANALYSIS

The preceding chapters discussed extensively the levels of risk likely to be imposed over the next fifteen years by the use of carbon fiber composites in commercial aircraft. The levels of risk were analyzed primarily in terms of the probability of economic loss at the national level. Based on the national risk profile, the question arises of whether a control policy designed to reduce the risk from carbon fibers is required. Specifically, policymakers must determine, subsequent to an evaluation of the risk profile, whether a control policy is needed and what form it should take. However, before such questions are addressed, the broad issues of the relative effects of a carbon fiber release must be carefully analyzed. That is, a policy decision cannot be based solely on the aggregate risk profile.

This section will more closely examine the relative economic impacts of a carbon fiber release. We will disaggregate the national risk profile into its components, and we will examine which parties are most severely affected by the current status quo (or regime) and which may hypothetically be affected by a change in this status quo. This analysis leads to the identification of stakeholders. We define a stakeholder in a policy regime as a group, not under the policymaker's direct control, whose collective behavior can directly affect, or is directly affected by, the policy regime. A policy designed to reduce the risk of carbon fiber release cannot be implemented without an adequate understanding of the stakeholders involved and the knowledge of how any one policy affects them.

The policymaker, in order to identify the stakeholders under the current regulatory regime (the current state of the world), must determine those groups, such as households or industry, that are most severely affected by a carbon fiber release, as well as those groups most severely affected by any policy that regulates the use of carbon fiber. We might identify the first class of stakeholders as those threatened by potential loss due to an accident, and the second class of stakeholders as those threatened by economic loss due to a risk-reducing policy.

There are basically two policy regimes in which the policymaker or decision maker must identify the stakeholders. The first is the current regime where he decides to do nothing. In this case, the stakeholders most severely affected are those threatened by economic loss due to an accident. The other policy regime is where some control is implemented. The stakeholders in this case are those threatened by an economic loss due to this policy.

To identify the first class of stakeholders, namely, those groups most affected by the current risk from carbon fibers, we must decompose the risk profile into those groups and sets of industries that are threatened by economic loss due to a carbon fiber release. By analyzing the outputs of the risk simulation, we were able to categorize those key groups as shown in Table 12-1, which provides the information required to understand the interest each industry group has in a particular policy.

Table 12-1 shows the relative frequency of economic loss, and the relative severity of the aggregated losses for each facility category. Frequency of loss is a measure of the probability that a loss will be incurred in a particular facility category, and is determined primarily by the physical characteristics of an individual establishment. Severity of maximum aggregated loss pertains to the case where a maximum exposure is experienced by a category.

The first factor affecting frequency of loss is the mean failure rate of the equipment in the category. The second factor is the set of building transfer rates. These factors determine the likelihood for

a loss to occur given a particular outside dosage. The third factor is the location of facilities in the metropolitan area, relative to the airport and prevailing weather conditions.

Severity of maximum aggregated loss is determined by the costs of repair and operating losses for each facility, and the total number of facilities which could be affected. The distinction between frequency of loss and severity of loss can best be explained by the concept of a threshold level of outside dosage required to cause a loss. The frequency measures the probability of achieving the threshold level, and the severity measures the magnitude of the losses aggregated over all facilities, once the threshold is exceeded.

As Table 12-1 indicates, gas and electric utilities and the general merchandise retailing industry face both a high frequency of loss and high severity of loss. Accordingly, their expected aggregate loss is the greatest under the current situation. As we indicated in Chapter 9, the nature of loss for these two industries is primarily repair costs. Neither of these groups face loss of revenue to a great extent, nor high operating costs due to a disruption. On the other hand, their high frequency of loss is, in large part, due to the amount of equipment that is not protected by buildings.

Aside from the stakeholders mentioned above, the one group facing the highest aggregate loss is households. Indeed, within the high severity-low frequency group, households account for approximately 40-45% of the expected loss. This is due to the fact that houses and apartments are not well protected from carbon fiber penetration, and that households utilize electronic equipment that would suffer damage from carbon fiber exposure. Accordingly, the dollar loss is derived primarily from repairs. However, the frequency of losses is low since the estimated mean failure levels of household goods are quite high. Certainly within this category of high severity-low frequency loss, the household must be recognized as an important stakeholder. Under the current regime, this category, as well as the first two mentioned above, are subject to the highest risk.

TABLE 12-1

RELATIVE ECONOMIC LOSSES ACROSS INDUSTRIAL CATEGORIES*

		<u>Frequency of Loss</u>	
		High	Low
<u>Severity of Aggregate Loss</u>	High	(14) Gas and Electric Utilities (15) General Merchandise Retailer	(1) Households (25) (12) Telephone Company (16) Retail Grocers (5) Automobile Radios (21) Hospitals
	Low	(11) Airplanes at Airports (19) Computer Programming and Software Services, Data Processing (10) Computer Manufacturers (18) Business Services (20) Electronic R&D Labs, Universities, Colleges	All Other

*Numbers in parentheses indicate industrial categories. See Chapter 9.

These stakeholders, therefore, will gain the largest benefit from any policy that reduces the risks from carbon fibers. Another group of stakeholders who would benefit from risk reduction is the low severity-high frequency of loss category. The exposure to risk here, however, is uniformly distributed across all five industry groups. Further, the costs primarily represent repairs. Very little economic loss was experienced by the cost of lost revenue.

Although gas and electric utilities, general merchandise retailers, and households have an interest in risk reduction, unless they perceive the risks as being large, they will have little incentive to affect policy. On the other hand, any change in policy that might restrict the use of carbon fiber composites in commercial aircraft would affect the airlines, the fabricators of airframes and engines, aircraft brake manufacturers, and the fiber material manufacturers. The potential for lost revenue due to such a policy will be significantly larger and more certain than the expected losses under the current regime, as shown by the revenue data in Chapter 3.

It is important to note that the above discussion is not meant to imply that any policy is indeed required. Such a judgment must be based on a more extensive economic analysis of the benefits of carbon fiber use and the related costs. This cost/benefit analysis would include a similar stakeholder analysis applied to any alternative control policies that are suggested. In Section 12.6 below, we will discuss some of the possible approaches toward reducing the risk associated with carbon fibers.

12.6 RISK CONTROL OPTIONS

This study does not seek to draw conclusions about the need for risk reduction relative to carbon fiber releases. In this section, however, we address the possible options available to policymakers, in the event that the need does arise for means of controlling the risk. From the estimates of economic loss presented above, it is not clear whether such measures will be justified in the foreseeable future.

There are two fundamental approaches toward reducing risk. One is to reduce the probability of the event which creates the risk, and the other is to reduce the magnitude of the consequences of such an event. We will describe each of these approaches in turn.

12.6.1 Reduction of Conditional Accident Probability

In Section 12.4.1, it was mentioned that improvement of airport safety features will not necessarily produce a substantial decrease in the probability of an accident per operation. Indeed, if this were possible, then we would reduce the other, more direct risks associated with air carrier crashes. However, it may be possible to reduce the conditional probability that an accident results in the release of large amounts of carbon fibers. This might be accomplished in several ways:

- Use alternative materials instead of carbon fiber composites for aircraft structures.
- Develop CF composites with reduced flammability or improved binding resins to prevent release of fibers.
- Design aircraft in such a way as to minimize the probability of a large fire (e.g., rupture-proof fuel tanks.)
- Employ fire-fighting techniques which will minimize the extent to which released fibers can escape into the atmosphere (e.g., washing out fibers by spraying water above the fire).

12.6.2 Reduction of Economic Consequences

Assuming that carbon fibers have been released into the atmosphere, the extent of damage caused by these fibers may be reduced in several different ways:

- Develop production methods which will diminish the conductivity of carbon fibers.
- Improve building ventilation and filtration standards, to restrict entry of fibers into interior spaces.

- Increase the vulnerability thresholds of electronic equipment by either protecting them with sealed cabinets or applying conformal coating to exposed electrical leads.
- Minimize the economic losses due to equipment failure by developing rapid recovery procedures or providing backup equipment.

The latter approach would reduce the losses due to failures from any cause, and many industries already have contingency plans of this type. For example, most data processing services have developed disaster recovery plans which are expensive to maintain, but are important for continuity of business operation.[3] At vital installations such as hospitals and airports, emergency procedures of this type are mandatory. For this reason, many of the facility categories listed in Table 9-1 were expected to have low risk of a critical failure.

12.7 AREAS FOR FURTHER INVESTIGATION

The national risk profiles for economic losses from carbon fibers provide a useful estimate of the risk due to the utilization of CF composites in commercial jet aviation. We have shown how policymakers can evaluate the risks to various stakeholders based upon these profiles, despite the range of uncertainty that is necessarily present. Nevertheless there are certain issues which have not yet been fully resolved, and investigation of these issues may result in reduction of the uncertainty and development of more accurate risk estimates. These open areas are listed below:

- Carbon Fiber Utilization Forecasts - The projected amounts of carbon fiber on different aircraft used in this study were average figures. If more detailed estimates of fleet mix and variation in CF use were available, the amount of CF composite on board could be described more accurately by a frequency distribution.

- Carbon Fiber Involvement in Accidental Fires - Although we assumed that the CF would be involved in any accident with fire, in reality the fire may engulf only one portion of the aircraft, leaving the portion carrying CF untouched. NASA and the airframe manufacturers are presently pursuing an investigation to resolve this issue, and also to obtain better CF usage forecasts. The incidence of fuel deflagrations, or "explosions", is also being examined.
- Carbon Fiber Release and Dispersion - There are still many gaps in our understanding of the physics of CF release during a burn and its subsequent dispersion in the atmosphere. NASA and other investigators are continuing to conduct tests in order to better determine the mass released under real accident conditions, the spectrum of fiber sizes that are released, and the effect of convection in the thermal plume upon the height and dimensions of the resulting fiber cloud.
- Vulnerability of Equipment - The inadequacies of currently available data on vulnerability were described in Chapter 8. Apart from the need for more thorough testing of vulnerability thresholds, there is also a need to explore certain areas in which little or no testing has been conducted. The issue of post-exposure vulnerability, for equipment that is activated long after exposure, is still poorly understood. To address this issue may require taking into account the phenomenon of deposition, and developing concentration-dependent failure models.
- Potential Shock Hazard - This open area was discussed in Section 12.3 above.
- Detailed Economic Analysis - A more accurate estimate of potential losses in various industries would require detailed investigation on an industry-by-industry basis. The issues of concern have already been discussed in Chapter 9.
- Growth of Electronics - As pointed out in Section 12.4, there is a need to explore both the increase in electronic devices and the changes in vulnerability characteristics of these devices over the next fifteen years.

- Detailed Analysis of Airports - Although this study focused a great deal of attention upon airports, there are still some remaining open areas. The vulnerability of an airport to disruption from carbon fibers involves more than the potential failure of equipment. Precautionary measures may be necessary in the aftermath of a CF exposure in order to ensure that aircraft and other sensitive equipment are decontaminated, even though they may not have failed. The resulting changes in operating procedures might cause business interruption, or at least substantial expense. These costs were not quantified in our model.
- Improve Confidence Bounds - Finally, sharper confidence bounds could be obtained for the risk profile by performing additional sensitivity runs for each of the important variables, and by running a larger number of iterations of the simulation model.

12.8 REFERENCES

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PHASE I

AN ASSESSMENT OF THE RISKS PRESENTED
BY THE USE OF CARBON FIBER COMPOSITES
IN COMMERCIAL AVIATION

Volume II: Supporting Appendices

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A. RISK MEASUREMENT METHODOLOGY

A.1 INTRODUCTION

The methodology described below served as a basis for the investigation of the various components of risk, and supplied a framework in which these components could be integrated. For the sake of generality, this methodology included a separate quantification for fatalities due to shock hazards. However, as explained in Chapter 12, we implemented only that portion dealing with economic losses. The shock hazard potential was estimated without resorting to a detailed simulation approach.

A.2 MATHEMATICAL NOTATION

The following symbols will be used in the subsequent derivation:

- A = Air carrier operational category (aircraft type; take-off or landing)
- T = Accident type (substantial damage or total destruction explosion and fire)
- Q = Vector of carbon fiber release characteristics (rate or height of release, mass, settling velocity, etc.)
- X = Geographic coordinates of exposed object relative to origin of accidental release (one of forty sectors).
- W = Weather, terrain, and atmospheric conditions (wind, precipitation, atmospheric stability, turbulence, etc.)
- B = Class of buildings or facilities exposed (ventilation properties and facility category)
- H = Class of electronic equipment exposed (residential, power, switching, etc.)
- V = Coordinates of accident location relative to the airport runway
- i = airport index
- Z = (T,A,V,W) Specific accident characteristics vector
- E = Exposure (integral of concentration over time)

TF = Transfer function for building penetration

P_Y = Probability distribution function for any variable Y

L = Dollar costs

S = Economic losses aggregated

$\bar{S}$ = Fatalities

A.3 METHODOLOGY DERIVATION

From forecasts of carbon fiber usage, one may compute the vector of fiber characteristics Q, given accident type T and aircraft operation category A,

$$= Q(T, A)$$

Using the appropriate dispersion model, we then obtain the exposure, or dosage of CF at location X given fiber characteristics and atmospheric conditions:

$$E(X|Q, W)$$

Since both Q and W are implied by Z, we will abbreviate the exposure as $E(X|Z)$.

Given the transfer function TF_B , the exposure inside building class B at location X is given by:

$$E_B(X|Z) = E(X|Z) \cdot TF_B$$

We now define the following quantities:

Probability of equipment in class H failing at exposure level of E (given by the exponential model in Chapter 8)

$$= P_H(E)$$

Probability of equipment being placed in lethal condition

$$= D_H(E)$$

Probability of fatal contact during lethal condition

$$= \pi_H$$

Probability of accident type T at location V relative to the runway,
for a given operation category A and weather and terrain condition W

$$= P_T (V,A,W)$$

The latter is a conditional probability, assuming that an accident
does occur.

In addition, we define the following deterministic variables,
as estimated from field work and census data:

Amount of vulnerable facilities in building class B at location
X, airport i

$$= M_i (X|B)$$

Amount of vulnerable outdoor equipment of class H at
location X, airport i

$$= M_i (X|H)$$

Amount or numbers of equipment of class H in facility class B

$$= G (H|B)$$

Losses due to failure of a unit of equipment class H within
building class B

$$= L_P (B,H) \text{ dollars; } L_D (B,H) \text{ fatalities}$$

Losses due to failure of a unit of outdoor equipment class H

$$= L_P^O (H) \text{ dollars; } L_D^O (H) \text{ fatalities}$$

For a specific airport i and accident vector Z, we have the
probability of an accident having characteristics Z at airport
i:

$$P_i (Z) = P_T (V,A,W)$$

(NOTE: This was adjusted to reflect airport differences, as
explained in Chapter 7.)

Now, using the above data, we can compute:

Consequences of accident with characteristics Z occurring at airport i:

Dollar loss due to failure of equipment H in buildings B

$$= S_i(Z, B, H) = \int_X P_H \left[E_B(X|Z) \right] \cdot M_i(X|B) G(H|B) L_P(B, H)$$

Fatalities due to failure of H in B

$$= \bar{S}_i(Z, B, H) = \int_X D_H \left[E_B(X|Z) \right] \Pi_H \cdot M_i(X|B) G(H|B) L_D(B, H)$$

Dollar loss due to failure of outdoor equipment H

$$= S_i^O(Z, H) = \int_X P_H \left[E(X|Z) \right] M_i^O(X|H) L_P^O(H)$$

Fatalities due to outdoor failure of H

$$= \bar{S}_i^O(Z, H) = \int_X D_H \left[E(X|Z) \right] \Pi_H M_i^O(X|H) L_D^O(H)$$

Hence, total consequences of Z are:

$$\text{(dollars)} \quad S_i(Z) = \sum_H S_i^O(Z, H) + \sum_{B, H} S_i(Z, B, H)$$

$$\text{(lives)} \quad \bar{S}_i(Z) = \sum_H \bar{S}_i^O(Z, H) + \sum_{B, H} \bar{S}_i(Z, B, H)$$

Probability of experiencing total consequences s:

$$\text{(dollars)} \quad r_i(s) = \sum_Z \left\{ P_i(Z) \mid S_i(Z) = s \right\}$$

$$\text{(lives)} \quad \bar{r}_i(s) = \sum_Z \left\{ P_i(Z) \mid \bar{S}_i(Z) = s \right\}$$

Conditional risk profile for airport i

= Probability of consequences exceeding s:

$$\text{(dollars)} \quad R_i(s) = \int_s^\infty r_i(\sigma) d\sigma$$

$$\text{(lives)} \quad \bar{R}_i(s) = \int_s^\infty \bar{r}_i(\sigma) d\sigma$$

The mixture and convolution methods used to combine individual airport risk profiles into a national risk profile are discussed in Chapter 11.

B. FIELD SURVEYS

B.1 Field Work Objectives

The purpose of our field work was to obtain information that would support the building penetration analysis in Chapter 7 and the economic analysis in Chapter 9. Since we were concerned with an 80 kilometer radius of exposure, the characteristics of exposed areas were expected to be relatively similar from one city to another. The major differences that we expected were in the average age of buildings and in the density of urban development. Thus, we anticipated appreciable differences between a fairly old Northeast Corridor metropolis with a dense inner core, and a sprawling, modern Southwestern city. Of course, climate differentials were taken into account in determining accident probabilities and release conditions (Chapters 4 and 5). The characteristics that we sought to identify in our field work had to do with the presence of equipment in potentially vulnerable facilities, their ventilation practices, and their recovery capabilities.

To accomplish this characterization, we decided to perform field work in at least three cities representing the range between "new, sparse" and "old, dense." The first city to be studied was Boston, since it is fairly representative of the latter extreme, and happened to be conveniently accessible. Due to the broad exposure radius, we did not examine specific areas in great detail. Instead we sought appropriate examples of various types of facilities, which then served as a basis for generalization. Our field experience in Boston also served as a test of the feasibility of gathering the desired data, and helped to set the scope of effort in subsequent visits to other cities.

Our objectives were of two types -- establishing classification systems and gathering data for prototype facilities. The field work objectives can be summarized as follows:

- Establish several classes of vulnerable equipment, each having different failure characteristics and costs.
- Establish several classes of residential, commercial or municipal establishments, each having different types

of vulnerable equipment. Estimate the amount of equipment inside a building of each class.

- Evaluate the typical direct costs of failure for each equipment class, and the indirect costs associated with equipment failure for each facility class.
- Identify types of facilities which may have unusually high losses, such as hospitals, and find methods of enumerating them for various exposed zones of the city and surroundings.
- Identify failure modes and costs associated with equipment located at the airport, allowing for extrapolation to other airports.
- Characterize the range of possible filtration and ventilation systems associated with buildings of different classes.

B.2 FIELD SURVEY METHODOLOGY

In general, vulnerable facilities were expected to fall into two categories:

- Broadly distributed facilities with moderate loss potential (e.g., residences, retail stores).
- Sparsely distributed facilities with high loss potential (e.g., hospitals, airports).

The strategy of our field work was largely to look at examples of the latter category. In each case, we were seeking several types of information:

- Numbers and types of vulnerable equipment located in the facility.
- Ventilation and filtration characteristics of the facility which affect such equipment.
- Costs of replacement or repair of equipment in the event of failure.
- Costs of business interruption due to such a failure.

In addition, we strove to identify those facility types which might be considerably different between cities, to obtain a better cross-section of penetration and loss parameters.

There are two components of risk from carbon fibers pertaining to various types of business or industry. One is the general risk, common to nearly all facilities, due to possible failure of office equipment, computer installations, cash registers, etc. Second is the particular risk imposed upon users or producers of highly vulnerable equipment, where the impact on total business operations may be far greater.

The Standard Industrial Codes (SIC) provide major classifications of businesses, and we addressed the following classes:

- Manufacturing
- Transportation, Communication, Utilities
- Retail Trade
- Financial
- Services

In terms of general risks, we took into account process control systems in Manufacturing, point of sale terminals in Retail Trade, and elevators, computer installations and office equipment for nearly all classes. A large part of this work was done through in-house research, once the equipment characteristics had been identified.

Within each SIC class, there were specific types of facilities which we identified as worthwhile for field visits. Most of these were of a singular nature, being few in number, and have a potential for high losses due to their reliance on electronic equipment. The list included:

- Air Traffic Control Centers
- Hospitals
- Post Offices
- Radio/TV Stations
- Telephone Exchanges
- Research and Development Laboratories
- Manufacturers of Electronic Devices

Rather than making a complete survey of such facilities, we attempted to visit some typical examples, and obtain enough information to allow general inferences about the extent of possible impacts.

To structure our field surveys, we developed two questionnaires - one to address vulnerable equipment and the other to address building penetration. These were used as a guide during interviews with facility personnel. The questionnaires are presented below:

B.3 INTERVIEW QUESTIONNAIRES

Equipment Vulnerability

Damage to electronic equipment from C-F is most prevalent in the lower voltage circuitry areas such as printed circuit boards and particularly in the vicinity of connectors. High voltage areas such as the power supply or high voltage section of TV's and data display terminals have some level of a self clearing action for low level exposures. But even here, failures can occur from high exposures. In facilities visits, we are particularly concerned with certain basic questions. The remaining data is to help us be more complete but the prime data is a necessity.

- What is the equipment (TV, display terminal, mini-computer, radio receiver, transmitter, etc.)?
- How big is it (desk-top, size of a filing cabinet, etc.)?
What is the approximate installed value or cost?
- What is the significance of a failure such as a defective component, broken wire, or failure such as pouring a glass of water into the equipment?
- What would be typical down-time and repair cost for a failed component?

For more detailed data we would want more specific information.

- Equipment Type - Proper terminology of equipment and its approximate age.
 - Function of the equipment.
 - Cooling provisions, fans, filters.
 - Description of physical format and installation. Is it in cabinets, in racks, how many sections in the rack?
 - Describe construction, printed circuit boards, random wired, modular, etc.
 - What is circuit technology, integrated circuit, MOS, bipolar, transistors, tubes.
 - What voltage levels are used and where? Low voltage (less than 24V dc, AC line power, high voltage such as for CRT displays).
 - Is there any rotating machinery involved?
 - Are there relays? Are they open or dust cover protected?
 - What is the normal repair experience? Frequency of outages and costs to repair?
 - Do any of the personnel have any guess as to the extent of damage that may be caused by tossing a fistful of short conductive fibers into the equipment?

BUILDING PENETRATION QUESTIONNAIRE

Introduction

Buildings with closed windows and doors, and well-filtered air supplies, significantly attenuate interior exposures due to contaminants in outdoor air. Conversely, buildings with many open doors and windows may only marginally provide a "cleaner" internal environment. An important part of our work therefore involves an assessment of the degree to which exposures may be attenuated by building, building use, and ventilation system characteristics.

In the following, a number of questions are listed which will allow us to qualitatively and quantitatively accomplish our objectives. The questions generally pertain to the entire building. However, where possible, we **would** attempt to focus upon specific areas housing vulnerable equipment.

Infiltration and Natural Ventilation

1. Are windows openable, or are they sealed?
2. If openable, are they opened during pleasant weather or at other times?
3. How many windows are typically open on a building side? How large are the open gaps? Are the windows screened?
4. Are doors to the outside propped open in pleasant weather?
5. Do entrances for the public involve interior and exterior doors?
6. Are there any sort of garage doors or such which open directly to vulnerable areas? Are they usually open?
7. Is the building considered to be of "tight" construction, or have drafts and leaks been noticed around windows and doors in cold weather?

Ventilation System Characteristics

1. Is the building air-conditioned or heated with a forced-air ventilation system?

2. How much fresh air is "blown" into the building per minute time (e.g., cubic feet per minute)?
3. Is the air filtered? If so, we would like to know:
 - a. Manufacturer, model and type of filter(s).
 - b. Rated efficiency on "dust spot" efficiency basis (or any other basis).
 - c. Number of filters in series if more than one.
4. How much, if any, air is exhausted from the building, passed through filters, and returned to the interior? In other words, how much air is recirculated?
5. Is the "mix" of fresh and recirculated air always kept the same, or are adjustments made for different seasons? Please describe adjustments.
6. Some ventilation systems are intentionally designed to force an excess amount of air into certain building spaces. This causes an incremental (i.e., positive) pressure in the building which reduces the amount of non-conditioned air leakage in. Is this practice employed anywhere in the building? Please describe where and why.
7. Are negative pressures maintained in any area? Why?
8. What are the hours of operation of the ventilation system? How many days per week?
9. How is the air distributed throughout the building? Are there inlet and outlet ports in every room?

Building Characteristics

1. What's the floor area of interior building spaces?
2. How high is the ceiling?
3. Are the floors carpeted?

Vulnerable Resource Areas

1. Are any special precautions taken to keep the air clean in the vicinity of electronic equipment?
2. Do items of electronic equipment have cabinets with filters (obtain characteristics if possible) on openings to the inside? Is there a fan to draw air through the cabinet? Alternatively, is the equipment completely sealed against internal contamination?

3. Do they vacuum or sweep the floors? How often?
4. Is there anything different about rooms with vulnerable equipment? Pay attention to doors, windows, floor coverings, ventilation system characteristics, etc. Also, consider the locations of power conditioning equipment, emergency generators, telephone switching gear, and other such equipment which may be in non-ventilated basements or maintenance areas.

General Observations

Provide your general and overall impression as to how and why uncleaned outdoor air may reach the vicinity of vulnerable equipment.

B.4 FIELD SURVEYS CONDUCTED

To select cities for site visits, after our initial Boston survey, we examined those cities classified as having medium or large hub airports. The criteria for selection included: age of the city, climate, terrain, industry, airport classification (instrumentation different from Logan), and population density. Our final choice narrowed down to two cities: Birmingham, Alabama, and Phoenix, Arizona. Birmingham's medium hub airport is landlocked, and has less sophisticated equipment than Boston's Logan Airport. The steel industry has facilities in the area, and Birmingham's climate differs significantly from Boston's. Birmingham is located on the southern boundary of the Appalachian Mountain Range.

Phoenix is a new city, with a landlocked, large hub airport. The flat terrain differs significantly from Boston's. Being in the sunbelt, Phoenix is growing in population, yet the population density is lower than most eastern cities. Since it is a fairly young city, it typifies what future cities might look like, and in this regard can be used for future scenario work. The dry, hot climate would be a contrast to the warm, humid weather of Birmingham and Boston's erratic New England weather extremes.

An additional site visit was made to Greenville, South Carolina, to increase our sample of airport facilities, and also to visit a textile plant, which was not possible at the other sites. Other miscellaneous field work was conducted by telephone, based upon referrals.

The specific facilities which were contacted at each field survey site are listed below:

Boston Massachusetts

Hospitals - Massachusetts General Hospital

- Tufts New England Medical Center

Ventilation Systems - Farr Commercial Products (air filters)

- Air Engineering, Inc.

Airport Facilities - Massport Engineering

- Delta Reservations Center

- Logan Control Tower

- Eastern Airlines Hangar and Terminal

Post Office - South Postal Annex (sorting)

Electronics Manufacturer - Data General

FAA Control Center - Nashua, New Hampshire

Payne Elevator Co.

WCOZ-FM Radio transmitter

WROR Radio transmitter

WEEI-FM Radio transmitter

WHDH Radio transmitter

WCVB-TV Studios and transmitter

WHDH/WCOZ Studios

New England Telephone Company

Phoenix, Arizona

Sky Harbor International Airport - Control tower

- TRACON Building

KOOL Radio and TV (CBS affiliate)

St. Joseph's Hospital

Arizona Electronics Standards Laboratories, Inc.

Birmingham, Alabama

Birmingham Municipal Airport - Control Tower

Steel Mills - U.S. Steel, Inc.

- Southwestern Steel Corp.

University of Alabama Medical Center

Greenville, South Carolina

Greenville - Spartanburg Airport - Control Tower

J. P. Stevens, Inc. (Textile Plant)

Other Telephone Surveys

Federal Reserve Bank - Electronic Funds Transfer, Atlanta, Ga.

National Elevator Institute, New York, New York

Carrier Corporation - Air Conditioning, Syracuse, New York

B.5 SUMMARY OF RESULTS

Detailed trip reports were prepared, describing our findings at each of the facilities visited or contacted. These are too voluminous to reproduce here, but they were forwarded directly to NASA for future reference.

The trip reports were reviewed carefully, and the results were incorporated into our assumptions and analyses for the areas of building penetration and economic analysis. A highly detailed interpretation of these results for various categories of facilities may be found in Appendix F. The implications for economic loss data are summarized in Chapter 9 and in Appendix G.

C. ACCIDENT STATISTICS

C.1 INTRODUCTION

This appendix presents some of the data and analytic results which were used to support the accident probability analysis. These include distributions of accident location, a list of the accident rates for the large and medium hubs, and a list of adjustments to the accident rates for the 26 large hubs.

C.2 LOCATION DISTRIBUTIONS

The following tables were utilized for location distributions, and to run goodness of fit tests. Distances are tabulated in miles because of NTSB reporting practice.

TABLE C-1

DISTANCES FOR TAKEOFF OR LANDING SUBSTANTIAL DAMAGE
ACCIDENTS (NO RESTRICTION TO FIRE)

	<u>ACTUAL</u>	<u>EXPECTED GIVEN EQUATION</u>
On Airport	142	
In Traffic Pattern	6	
≤ 1/4 mile (0.4 km.)	4	2.32
≤ 1/2 mile (0.8 km.)	1	1.84
≤ 3/4 mile (1.2 km.)	0	1.45
≤ 1 mile (1.6 km.)	1	1.15
≤ 2 miles (3.2 km.)	3	2.64
≤ 3 miles (4.8 km.)	2	1.03
≤ 4 miles (6.4 km.)	0	.40
≤ 5 miles (8.0 km.)	0	.16

$$\chi^2 = 4.6$$

TABLE C-2

DISTANCES FOR TAKEOFF AND LANDING IN TOTAL
DESTRUCTION ACCIDENTS WITH FIRE
TAKING PLACE OFF AIRPORT

	<u>TOTAL</u>	<u>TAKEOFF</u>	<u>LANDING</u>	<u>EXPECTED TOTAL GIVEN EQUATION</u>
Airport	26	10	16	
Traffic Pattern	4	1	3	
≤ 1/4 mile (0.4 km.)	1	0	1	1.3
≤ 1/2 mile (0.8 km.)	1	1	0	1.14
≤ 3/4 mile (1.2 km.)	1	0	1	1.02
≤ 1 mile (1.6 km.)	3	1	2	.92
≤ 2 miles (3.2 km.)	1	0	1	2.83
≤ 3 miles (4.8 km.)	2	0	2	1.84
≤ 4 miles (6.4 km.)	1	0	1	1.2
≤ 5 miles (8.0 km.)	1	0	1	.78
> 5 miles (8.0 km.)	2	0	2	
Unknown	1	0	1	

$\chi^2 = 7.89$ based on the distance categories for which expected frequencies are given.

The on-airport percentages are substantially different for takeoff and landing. However, the three off-airport takeoff accidents do not show a large difference from the off-airport landing accidents distribution.

C.3 ACCIDENT RATES

The following tables list accident rates for the large and medium hubs. Table C-4 presents the conditional probability of an accident occurring at each large hub, given that it occurs somewhere in the nation.

TABLE C-3

ACCIDENT RATES FOR SELECTED AIRPORTS

State	City	Airport	July 1976 - June 1977 Departures	1968-1976 Crashes	* Rate Per Million Operation**	Prob. VFR
Alabama	Birmingham	Municipal	20,990	0	0	.893
Alaska	Anchorage	International	15,936	4	14	NA
Arizona	Phoenix	Sky Harbor Intl.	46,684	0	0	NA
Arizona	Tucson	International	17,085	0	0	NA
Calif.	Los Angeles	International	143,433	2	.8	.85
Calif.	San Diego	Lindbergh	24,221	0	0	.902
Calif.	San Francisco	International	102,131	5	2.7	.921
Colorado	Denver	Stapleton Intl.	113,753	6	2.9	.948
Conn.	Hartford	Bradley Intl.	28,544	1	1.9	.865
DC	Washington	Dulles Intl.	25,919	3	6.4	.887
DC	Washington	National	104,070	4	2.1	.926
Florida	Jacksonville	International	20,822	0	0	.913
Florida	Ft. Lauderdale	FLL-Hollywood	37,252	2	3.0	NA
Florida	Miami	International	83,110	16	10.7	.981
Florida	Orlando	McCoy AFB	37,312	0	0	NA
Florida	Tampa/St. Ptsb.	Tampa Intl.	55,393	0	0	NA
Florida	West Palm Bch.	Palm Beach Intl.	16,680	0	0	NA
Georgia	Atlanta	Heartsfield Intl.	216,142	3	.8	.871
Hawaii	Hilo	Gen. Lyman Fld.	9,058	0	0	.979
Hawaii	Honolulu	Honolulu Intl.	45,813	3	3.6	NA
Hawaii	Kahului, Maui	Kahului	19,239	0	0	NA
Hawaii	Lihue Kanai	Lihue	12,221	0	0	NA
Illinois	Chicago	O'Hare Intl.	290,374	10	1.9	.882
Indiana	Indianapolis	West Cook	37,599	1	1.5	.874
Kentucky	Louisville	Standiford Fld.	27,655	0	0	.92
Louisiana	New Orleans	Moisant Fld.	45,990	1	1.2	.907
Maryland	Baltimore	Balt./Wash. Int'l.	34,665	0	0	.884
Mass.	Boston	Logan Intl.	97,635	8	4.6	.878
Michigan	Detroit	Metro.Wayne Cty	78,147	1	.7	.871
Minn.	Mnpls/St. Paul	International	66,218	0	0	.907
Missouri	Kansas City	International	56,304	1	1.0	NA
Missouri	St. Louis	Lambert Field	87,495	4	2.5	.897
Nebraska	Omaha	Eppley Field	23,352	0	0	.913
Nevada	Las Vegas	McCarron Field	52,860	2	2.1	NA
Nevada	Reno	International	13,528	0	0	NA
N.J.	Newark	Newark Airport	64,355	3	2.1	.883
N.M.	Albuquerque	Sunport/Kirkland	21,969	0	0	NA
New York	Buffalo	Buffalo Int.	37,455	2	3.0	.862
New York	NYC	JFK Int.	109,210	18	9.2	.880
New York	NYC	Laguardia	131,988	3	1.3	.881
New York	Rochester	Monroe County	23,149	0	0	.888
New York	Syracuse	C. E. Hancock	16,528	0	0	.852
N.C.	Charlotte	Douglas	34,278	1	1.6	.916
N.C.	Greensboro	Regional	15,135	2	7.3	.937
N.C.	Raleigh/Durham	R/D Airport	15,642	1	1.9	.940

*Total destruction and substantial damage accidents.

**Departures are extrapolated to reflect all operations over a nine-year period.

NA - Not available, estimated where necessary.

<u>State</u>	<u>City</u>	<u>Airport</u>	<u>July 1976 - June 1977 Departures</u>	<u>1968-1976 Crashes *</u>	<u>Rate Per Million Operation**</u>	<u>Prob. VFR</u>
Ohio	Cincinnati	Greater Cin.	36,391	0	0	.870
Ohio	Cleveland	Hopkins	58,312	3	2.9	.881
Ohio	Columbus	Port Columbus	27,538	0	0	.888
Ohio	Dayton	J. M. Cox	24,620	0	0	.852
Oklahoma	Okla. City	Will Rogers	24,630	0	0	.916
Oklahoma	Tulsa	International	21,646	0	0	.937
Oregon	Portland	International	38,862	1	1.4	.940
Penn.	Phila.	International	67,258	4	3.3	.883
Penn.	Pittsburgh	Greater Pittsbgo.	90,337	2	1.3	.863
Tenn.	Memphis	International	56,190	1	1.0	.927
Tenn.	Nashville	Metropolitan	28,282	0	0	.911
Texas	Dallas/Ft.W.	Greater SW Reg'l	145,827	3	1.1	NA
Texas	El Paso	International	13,946	0	0	NA
Texas	Houston	Intercontinental	63,774	2	1.7	NA
Texas	San Antonio	International	20,969	0	0	.852
Utah	Salt Lake City	International	34,247	1	1.6	.946
Virginia	Norfolk	Regional	18,429	0	0	.870
Wash.	Seattle	Seattle/Tacoma	54,168	1	1.0	.906
Wash.	Spokane	International	14,371	1	3.9	NA
Wisc.	Milwaukee	Gen. Mitchell	38,802	0	0	.871
P.R.	San Juan	San Juan Intl.	15,176	2	.7	NA

TABLE C-4

FACTORS USED IN COMPUTING CONDITIONAL ACCIDENT PROBABILITIES
OF 26 HUB AIRPORTS

	<u>ANNUAL JET DEPARTURES</u>	<u>FOREIGN ADJUSTMENT</u>	<u>ESTIMATED 1993 JET OPERATIONS</u>	<u>WEATHER ADJUSTMENT</u>	<u>CONDITIONAL PROBABILITY</u>
Atlanta	210,405	1.03	433,434	1.09	.096
Boston	82,643	1.04	171,897	1.06	.036
Chicago	272,427	1.10	599,339	1.04	.128
Cleveland	56,611	1.03	116,618	1.05	.025
Dallas	139,985	1.03	288,369	1.00	.058
Denver	98,023	1.03	201,927	.78	.032
Detroit	69,013	1.03	142,166	1.09	.031
Honolulu	45,813	1.10	100,788	.80	.016
Houston	62,931	1.03	129,637	1.00	.026
Kansas City	47,076	1.03	96,976	.99	.019
Kennedy	96,425	1.50	289,275	1.05	.062
Laguardia	106,862	1.00	213,724	1.05	.046
Las Vegas	52,860	1.03	108,891	.79	.017
Los Angeles	141,664	1.10	311,660	1.17	.074
Miami	83,110	1.50	249,330	.65	.033
Minneapolis	60,344	1.03	124,308	.95	.024
Newark	56,412	1.03	116,208	1.04	.025
New Orleans	45,821	1.10	100,806	.95	.019
Philadelphia	67,243	1.03	138,520	1.04	.029
Phoenix	44,262	1.03	91,179	.79	.015
Pittsburgh	85,801	1.03	176,750	1.12	.040
San Francisco	99,834	1.10	219,634	.89	.040
Seattle	54,166	1.10	119,165	.95	.023
St. Louis	80,468	1.03	165,764	.99	.033
Tampa	55,383	1.03	114,088	.80	.018
Washington	91,891	1.03	189,295	.87	.033

C.4 PRECIPITATION PROBABILITIES

As precipitation could have an effect on carbon fiber dispersion, we examined the conditional probability of precipitation given an accident. We did not, however, incorporate this probability in the model. Defining

$P(\text{PRECIP}|\text{ACC})$ = Probability of precipitation given an accident nationally

$P(\text{PRECIP}_i|\text{ACC}_i)$ = Probability of precipitation given an accident at airport i and using the basic probability laws relating events A, B, C ($\bar{B}$ indicates event "not B"),

$$P(A|C) = P(A \cap B|C) + P(A \cap \bar{B}|C)$$

$$P(A|B \cap C) = P(B|C) + P(A|\bar{B} \cap C)P(\bar{B}|C),$$

we have

$$\begin{aligned} P(\text{PRECIP}_i|\text{ACC}_i) &= P(\text{PRECIP}_i|\text{IFR}_i \cap \text{ACC}_i) \cdot P(\text{IFR}_i|\text{ACC}_i) \\ &\quad + P(\text{PRECIP}_i|\text{VFR}_i \cap \text{ACC}_i) \cdot P(\text{VFR}_i|\text{ACC}_i). \end{aligned}$$

We estimate $P(\text{PRECIP}_i|\text{IFR}_i \cap \text{ACC}_i)$ by national figures, i.e.,
 $\tilde{P}(\text{PRECIP}|\text{IFR} \cap \text{ACC}) = .63$ from national accident and weather data base.

Also, $P(\text{PRECIP}_i|\text{VFR}_i \cap \text{ACC}_i) \tilde{P}(\text{PRECIP}|\text{VFR} \cap \text{ACC}) = .17$. Thus,

$$P(\text{PRECIP}_i|\text{ACC}_i) = .63P(\text{IFR}_i|\text{ACC}_i) + .17P(\text{VFR}_i|\text{ACC}_i),$$

but by Bayes' theorem,

$$\begin{aligned} P(\text{IFR}_i|\text{ACC}_i) &= P(\text{ACC}_i|\text{IFR}_i)P(\text{IFR}_i)/P(\text{ACC}_i) \\ &\tilde{P}(\text{ACC}|\text{IFR})P(\text{IFR}_i)/P(\text{ACC}_i) \\ &= 4.52P(\text{ACC})P(\text{IFR}_i)/P(\text{ACC}_i). \end{aligned}$$

Likewise,

$$P(\text{VFR}_i|\text{ACC}_i) \tilde{P}(\text{ACC})P(\text{VFR}_i)/P(\text{ACC}_i).$$

Putting this together and using $P(\text{ACC}_i)$ from Chapter 4, Equation (4-1), gives

$$\begin{aligned}
 P(\text{PRECIP} | \text{ACC}_i) &= \frac{.63[4.52P(\text{ACC})P(\text{IFR}_i)] + .17[.58P(\text{ACC})P(\text{VFR}_i)]}{P(\text{ACC}_i)} \\
 &= \frac{.63(4.52)P(\text{IFR}_i) + .17(.58)P(\text{VFR}_i)}{4.52P(\text{IFR}_i) + .58P(\text{VFR}_i)}
 \end{aligned}$$

In Boston, for example, the probability of IFR (and below minimum) is

$$P(\text{IFR}_i) = .122$$

and

$$P(\text{PRECIP} | \text{ACC}_i) = .409$$

Note that this probability is larger than the unconditional probability of precipitation.

$$\begin{aligned}
 P(\text{PRECIP}_i) &= P(\text{PRECIP}_i | \text{IFR}_i)P(\text{IFR}_i) \\
 &\quad + P(\text{PRECIP}_i | \text{VFR}_i)P(\text{VFR}_i) \\
 &= .63 \times .107 + .17 \times .893 \\
 &= .22
 \end{aligned}$$

D. DISPERSION OF CARBON FIBERS RELEASED FROM AN AIRCRAFT ACCIDENT

D.1 PERSPECTIVE

In an accident involving an aircraft containing carbon fiber composite parts and resulting in a fire, the carbon fibers are likely to be released into the atmosphere. The dispersion of the fibers will be affected by the fire plume, prevailing wind, and the atmospheric turbulence. The fibers tend to settle to the ground because their density is higher than that of air. In this section the phenomenon of carbon fiber dispersion is discussed and models used to calculate the downwind fiber exposure contours are given. The sophistication of the models is commensurate with the level of detail available for the input data and the accuracy necessary for a risk analysis. The models developed in this Appendix are used in Chapter 6 of this report for purposes of the risk analysis. The nomenclature utilized in this Appendix and Chapter 6 is presented in Section D.5 of this Appendix. The References are provided in Section D.6.

D.2 INTRODUCTION

Carbon fiber composites are expected to be used in increasing quantities in various parts of commercial aircraft, since they have high strength-to-weight ratios. The carbon fibers used in the composites are electrically conductive. When electronic and electrical equipment are exposed to these fibers, there exists a possibility of electrical short circuit. Therefore, the release of carbon fibers consequent to an aircraft accident presents a potential risk to electrical and electronic equipment both in the vicinity of and in areas far from the accident site. The released fibers will be scattered over a wide area by atmospheric turbulent dispersion. Different areas downwind are exposed to different fiber exposure levels depending on a number of factors, including the atmospheric conditions, mass of fibers released, nature and height of release, fall rates of fibers, etc. To evaluate, therefore, the level of risk presented to different areas by potential carbon fiber releases, it is essential to understand the dispersive nature of the atmosphere for the fibers and the total areas exposed to carbon fibers. In effect, dispersion analysis is an important part of the risk analysis.

An aircraft accident which results in a fire and the burning of the parts of the aircraft will result in the burning of the epoxy binder in the carbon fiber composites. Under these conditions, the bared carbon fibers can be released by relatively mild agitation. An explosion at this stage will certainly scatter into the atmosphere carbon fibers of a spectrum of lengths. Structural collapse of aircraft following the fire may also provide enough agitation to release the fibers. The intense burning of the fuel and the epoxy and the large fire that may result in an aircraft accident is likely to draw in air at a high velocity and induce considerable turbulence within the fire. It is uncertain at present whether the high velocity of the air (10 to 15 m/s) and the intense turbulence in the fire are sufficient to release carbon fibers from burnt-out laminates.

The fibers used in the laminates are very small in diameter (7 to 8 microns), and are brittle. The short length, individual fibers (length in the range of millimeters up to a centimeter) have very low terminal velocities (1 through 5 cm/s) of fall in air. Clumps of fibers have higher fall rates (10 cm through 100 cm/s) and flakes of fibers have even higher fall rates. The fall rates by fiber size and category are shown in Table D-1. Because of the relatively slow settling velocities of individual fibers, they tend to remain in suspension in the atmosphere for considerable periods of time, when released into the atmosphere. Also, they tend to get carried up with hot plumes of gas generated by fires.

The fibers dispersed by the atmospheric transport processes may affect the open and exposed electrical equipment such as the electrical substations, motors, and other machinery. They can also be ingested into the buildings through the normal ventilation systems and possibly affect the electronic equipment and components within the buildings. Since the electronic component failure probability is a function of fiber exposure level, it is necessary to calculate the fiber exposure value at given locations down wind of an accident site. Such calculations are performed using the dispersion models described below.

TABLE D-1

Representative Terminal Velocities for Carbon
Fibers*

Category	Approximate Size	Fall Rate (m/s)
Single fibers	5 - 7 micron diameter	0.032
Lint		0.22
Brush/Clump		0.88
Blast Fragments	Width < 2 mm	1.52
Blast Fragments	Width 2-7 mm	1.67
	Length < 25 mm	
Blast Fragments	Width > 7 mm	1.89
	Length > 17 mm	

* Source: NASA (1978)

D.3 PHYSICAL PROCESSES IN THE DISPERSION OF CARBON FIBERS

Consider the scenario of an aircraft accident followed by a fire. Two types of burning can be pictured. In the first type of burning, it is assumed that the fuel tanks have breached due to the accident and that the spilled fuel is burning on the ground. Such a fire will last for a significant duration of time (few minutes to about 10 minutes) and consume the epoxy bonding on the composites. The fire generates a large hot gas plume which rises into the atmosphere. The carbon fibers may be released into the fire plume. Such a release scenario is identified by a "plume dispersion scenario." The phenomenon of plume rise including the physical principles and the available data have been discussed in detail by Briggs [D.1].

In the second type of burning, the fuel load of the aircraft may be partially spilled due to the accident and ignited. The resulting fire consumes the epoxy in the composites but the fire may not be large enough to cause the release of fibers into the fire plume. Conceivably, the fire can spread to as yet undamaged fuel tanks resulting in a very rapid and intense fire. An explosion can result which would scatter the burned composites and carbon fibers (CF). In general, a sudden ignition of large amounts of fuel or fuel-air mixture results in the formation of a fireball which rises into the air. Vickers and Lopez [D.10] have discussed the entrainment of fibers into the fireball resulting from an intense, short duration fire. Fibers entrained into the fireball will be released at different heights depending on the size and rate of rise of the fireball. This scenario of fiber release is termed the "explosive release." In this case it is assumed that all of the fibers are released into the atmosphere "instantaneously."

The instantaneously released fiber cloud moves downwind carried by the prevailing wind. At the same time the fiber cloud expands in size due to the dispersive nature of the atmospheric turbulence resulting in an overall reduction in the mean fiber concentration* within the cloud.

* Fiber concentration is equal to the number of fibers per unit volume of space.

Because the fibers are heavier than air, they tend to settle to the ground. Some of the fibers that have settled may be reentrained into the fiber cloud. However, there is a net settling out and this represents a depletion in the mass of fibers in the dispersing cloud. The size and location of footprints on the ground for different exposure levels depend on the total quantity of fibers released, type of atmosphere, release height and the size of the fibers. The details of the dispersion model based on the above physical picture are given in Chapter 6.

In the case of plume dispersion, the hot gas plume rises into the atmosphere. Because of the shear between the upward motion of the gases and the ambient air, mechanical turbulence is generated. Turbulence is also generated due to the thermal state of the hot plume. These two types of turbulence aid in the mixing of the ambient air and the hot gases ("entrainment"). The upward velocity of the plume is, therefore, continuously reduced. The prevailing horizontal wind then bends the plume. Once the plume bends over, it moves horizontally at nearly the mean wind speeds; however, the plume continues to rise relative to the ambient air aided by the buoyancy of the gases. The vertical rise of the now-almost-horizontal plume is inhibited if (a) the ambient air density is equal to that of the warm gases in the plume, and (b) the plume encounters an inversion layer. The air density in the atmosphere decreases with an increase in altitude. Inversion layers are formed in the atmosphere at locations where the temperature of the air increases with an increase in height (temperature gradient is positive). Such layers are extremely stable and tend to damp out any large turbulent motions.

In either of the above conditions, the plume reaches a "ceiling height." The carbon fibers in the gas plume tend to separate out from the warm gases and fall. The fibers are moved downwind by the wind at its speed. The fiber plume is also broadened by the atmospheric turbulence. Because of the simultaneous horizontal and vertically down motion of the fiber plume, it assumes a "tilted plume" configuration. Tilted plumes are discussed in greater detail by Pasquill [D.5]. Since the wind speed varies in the atmosphere, the tilt of the fiber plume also varies with distance. Once the center line of the fiber plume hits the ground, the

subsequent dispersion of the fibers is at the ground level. The above physical ideas are indicated schematically in Figure 'D-1.

In the above discussion on the physics of dispersion of carbon fibers, no reference was made to the scavenging effects of precipitation in the atmosphere. If there should be rain, snow or other types of precipitation during the time of dispersion of fibers in the air, a considerable fraction of the fibers are expected to be scavenged out of the dispersing cloud and deposited on the ground. No direct experimental evidence or data exist to quantify the rain and snow effects on carbon fibers. Fog, in general, may not have any direct effect on the dispersion of carbon fibers, except if the fibers act as nuclei for initiating precipitation from the fog.

D.4 REVIEW OF LITERATURE AND EQUATIONS RELEVANT TO CARBON FIBER DISPERSION

In this section the literature pertinent to the general problem of carbon fiber dispersion in the atmosphere is reviewed and important formulae are noted.

D.4.1 Classifications of Weather and Atmosphere

The dispersion of pollutants in the atmosphere is strongly dependent on the state of the atmosphere, i.e., on the turbulence level in the atmosphere. The diurnal heating and cooling cycles of the earth's surface, respectively, by solar radiation and nocturnal radiation to space influence the atmospheric conditions locally. The air in contact with the ground gets heated or cooled depending on the ground temperature. This heating and cooling of the atmosphere can extend from several hundred meters to several thousand meters.

In most dispersion problems the relevant atmospheric layer is that nearest to the ground varying in thickness between hundreds of meters to thousands of meters. Variations in both thermal and mechanical (shear induced) turbulence and in wind speed are greatest in the layer in contact with the surface. Turbulence induced by buoyancy forces in the atmosphere is closely related to the vertical temperature structure.

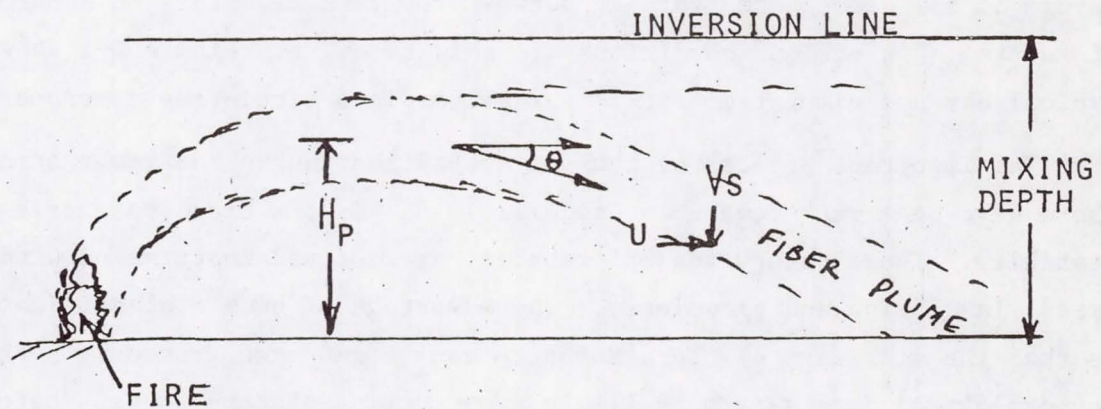


FIGURE D-1

SCHEMATIC ILLUSTRATION OF THE DISPERSION
OF CARBON FIBERS IN A FIRE GENERATED PLUME

When the temperature decreases at 9.8 K/km with height, the atmosphere is said to be "neutrally stable" because the vertical motions of air are neither damped nor amplified [D.2]. The rate 9.8 K/km is called the "dry adiabatic lapse rate." If the temperature decreases faster than the above rate, vertical motions are amplified and the atmosphere is said to be "unstable." Vertical motions are damped and the atmosphere is "stable" when the temperature decreases more slowly than the adiabatic lapse rate. When the temperature increases with height, as indeed happens in certain layers of the atmosphere (varying between few tens of meters to hundreds of meters), "inversion" conditions are said to exist. Figure D-2 shows typical day and night temperature variations in a cloud-free atmosphere.

The important effects of thermal stratification in the lower atmosphere have been represented by Pasquill [D.5] in six broad categories of stability. These categories of stability are defined in terms of wind speed, insolation and cloudiness. The advantage of such a classification is that the stability of the atmosphere can be inferred from only such meteorological data as are available from routine observations. The original six classifications by Pasquill have been modified by Turner [D.8, D.9] into 7 categories of atmospheric stability (A through G). Turner also indicates the method of determining the stability state of the atmosphere by knowing the wind speed, cloud cover, solar altitude (elevation angle of sun) and cloud ceiling. The relationship between the solar altitude and insolation class number is given in Table D-2a. Relationship between wind speed, insolation index, and stability class is given in Table D-2b. The STAR (stability array) program adopted by the National Climactic Center (of the National Oceanic and Atmospheric Administration) for recording the meteorological data from weather stations all across the U.S., uses the Turner system of atmospheric stability classifications [D.3].

Using the available dispersion data Pasquill has developed the relationship between vertical and horizontal standard deviations of spread and the downwind distance with the atmospheric stability as a parameter. Figures D-3a and D-3b show these relationships in a form revised by Gifford [D.4]. Based on numerical solution of two dimensional diffusion

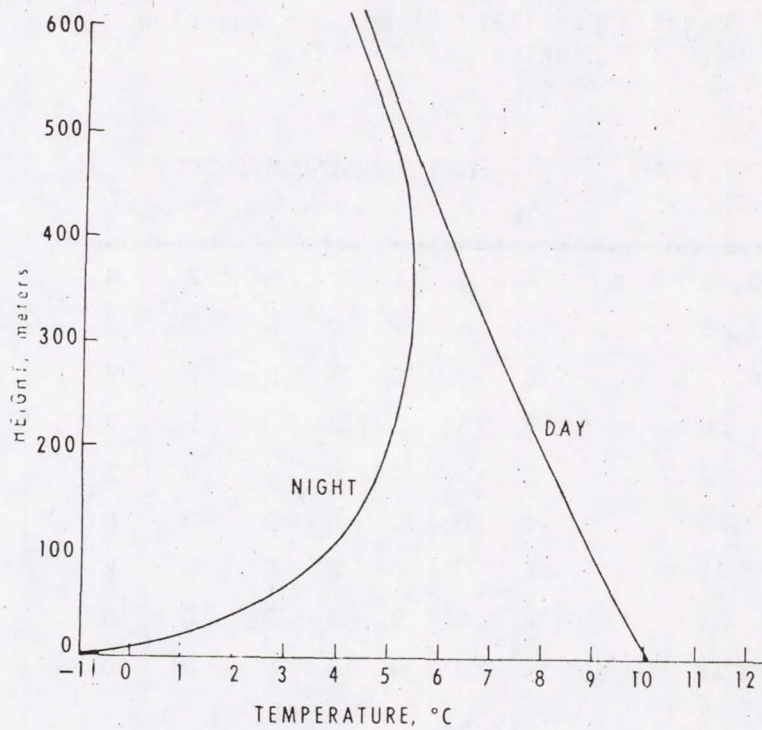


Figure D-2: Typical Day and Night Temperature Distribution in the Atmosphere
[From Turner (1970)]

TABLE D-2a

Pasquill Stability Class as a Function
of Net Radiation and Wind Speed

WIND SPEED (KNOTS)	NET RADIATION INDEX						
	4	3	2	1	0	-1	-2
0, 1	A	A	B	C	D	F	G
2, 3	A	B	B	C	D	F	G
4, 5	A	B	C	D	D	E	F
6	B	B	C	D	D	E	F
7	B	B	C	D	D	D	E
8, 9	B	C	C	D	D	D	E
10	C	C	D	D	D	D	E
11	C	C	D	D	D	D	D
≥ 12	C	D	D	D	D	D	D

TABLE D-2b

Insolation as a Function of Solar Attitude

SOLAR ALTITUDE (a)	INSOLATION	INSOLATION CLASS NUMBER
$60^\circ < a$	Strong	4
$35^\circ < a \leq 60$	Moderate	3
$15^\circ < a \leq 35$	Slight	2
$a \leq 15^\circ$	Weak	1

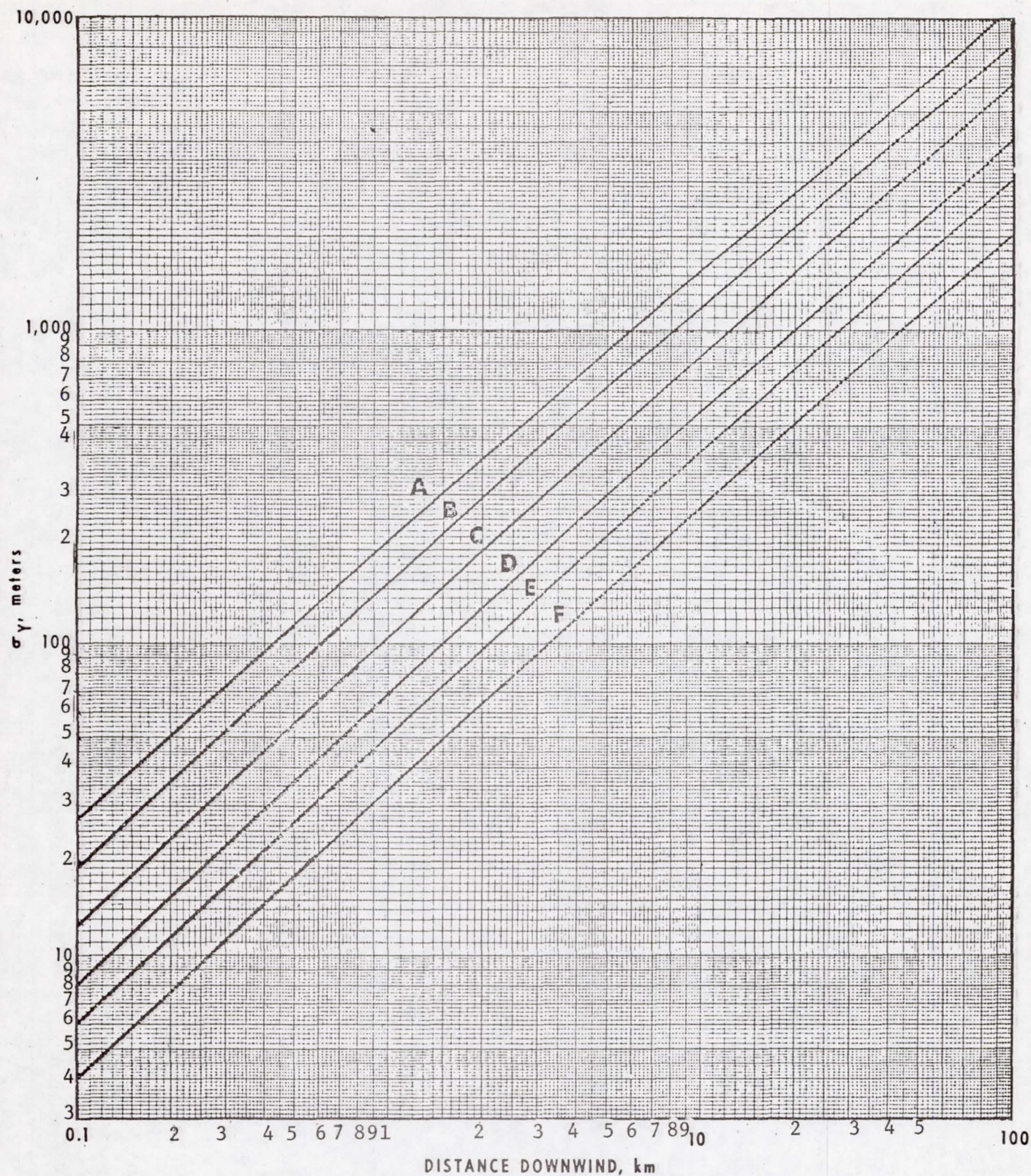


Figure D-3a: Horizontal Dispersion Coefficient as a Function of Downwind Distance from the Source

ATMOSPHERIC DISPERSION ESTIMATES

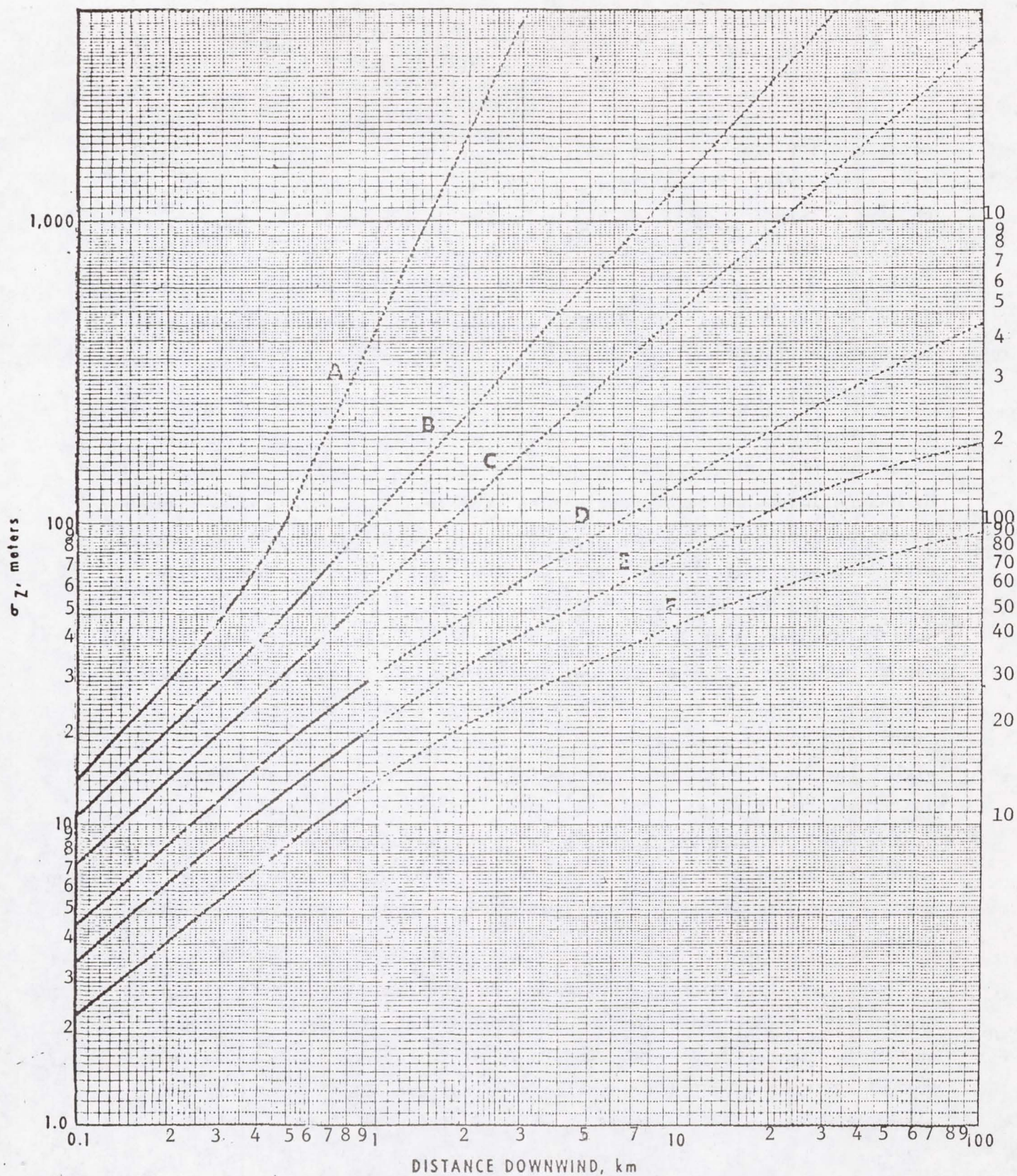


Figure D-3b: Vertical Dispersion Coefficient as a Function of Downwind Distance from the Source

equations for dispersion of pollutant near the ground, Smith [D.6] has revised the Pasquill stability categories to vary from very unstable (A) to very stable (G). Also he has developed curves to relate upward heat flux and wind speed to the stability category. This figure is reproduced in Figure D-4. Pasquill [D.5] also gives graphs using Smith's method to estimate the vertical dispersion coefficient for different aerodynamic roughness terrains and for different stability conditions.

The convective turbulent mixing in the atmosphere extends generally from ground up to a level which is the interface between the boundary layer and the stable overlying atmosphere. This interface is characterized by change in the temperature gradient (the gradient is less than adiabatic lapse rate) or some times by an inversion (in which the temperature actually increases with height). Overland vertical mixing will usually be effective up to this major inversion base for part of the day only, when surface heating is such as to generate convective motion of sufficient vigor. At other times of the day, and especially in periods of strong nocturnal radiative cooling of the surface, vertical mixing may be confined to a height well below the overhead inversion. The potential depth within the lower atmosphere over which a pollutant can be mixed uniformly is termed the "mixing depth". A representative diurnal variation of the mixing depth is shown in Figure D-5. The maximum mixing depths for several locations in the U.S. are shown in Figures D-6a and D-6b in the form of contour maps. These are averages of maximum mixing depths in the respective months over a few years.

The classification of the weather by the FAA for aircraft flight operations differs markedly from the classifications used by meteorologists and environmental engineers. The FAA classifications consist basically of two types, namely, VFR (visual flight rules) and IFR (instrument flight rule). IFR weather is defined as that condition in which the cloud ceiling is less than 300 m or visibility is less than 5 km or both [D.11]. The "ceiling" is defined as the lowest cloud base in which 3/4 of the sky is filled. VFR weather is defined as that condition in which the cloud ceiling and visibility are both above IFR values.

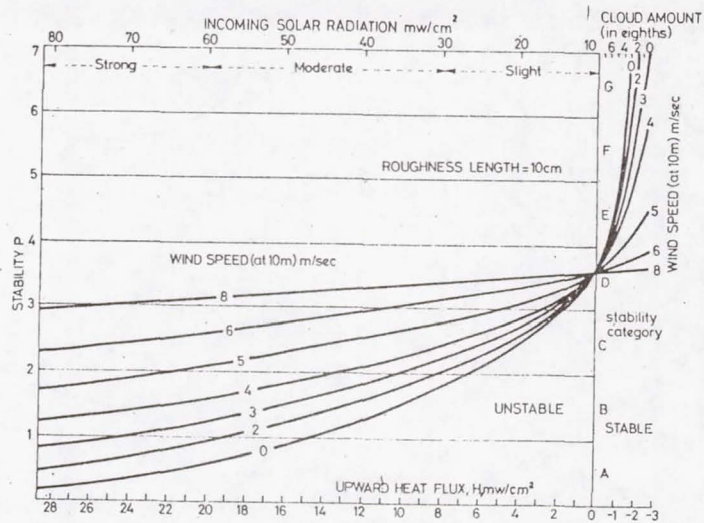


Figure D-4: Relationship Between Pasquill Stability Class, Wind Speed and Heat Flue from Ground. [D.6]

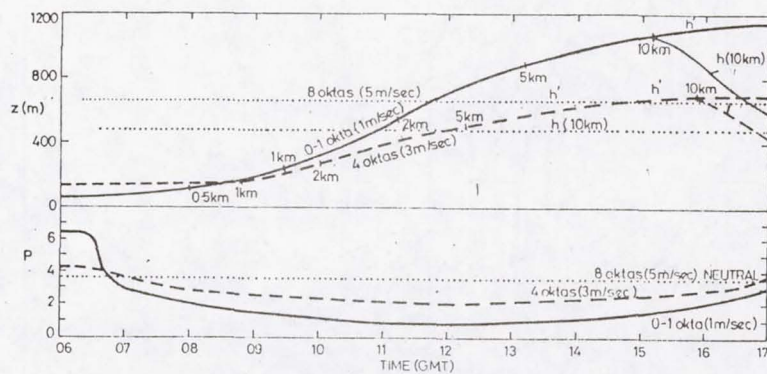


Figure D-5: Variation of Mixing Depth and Stability Index with Time of Day [D.5]

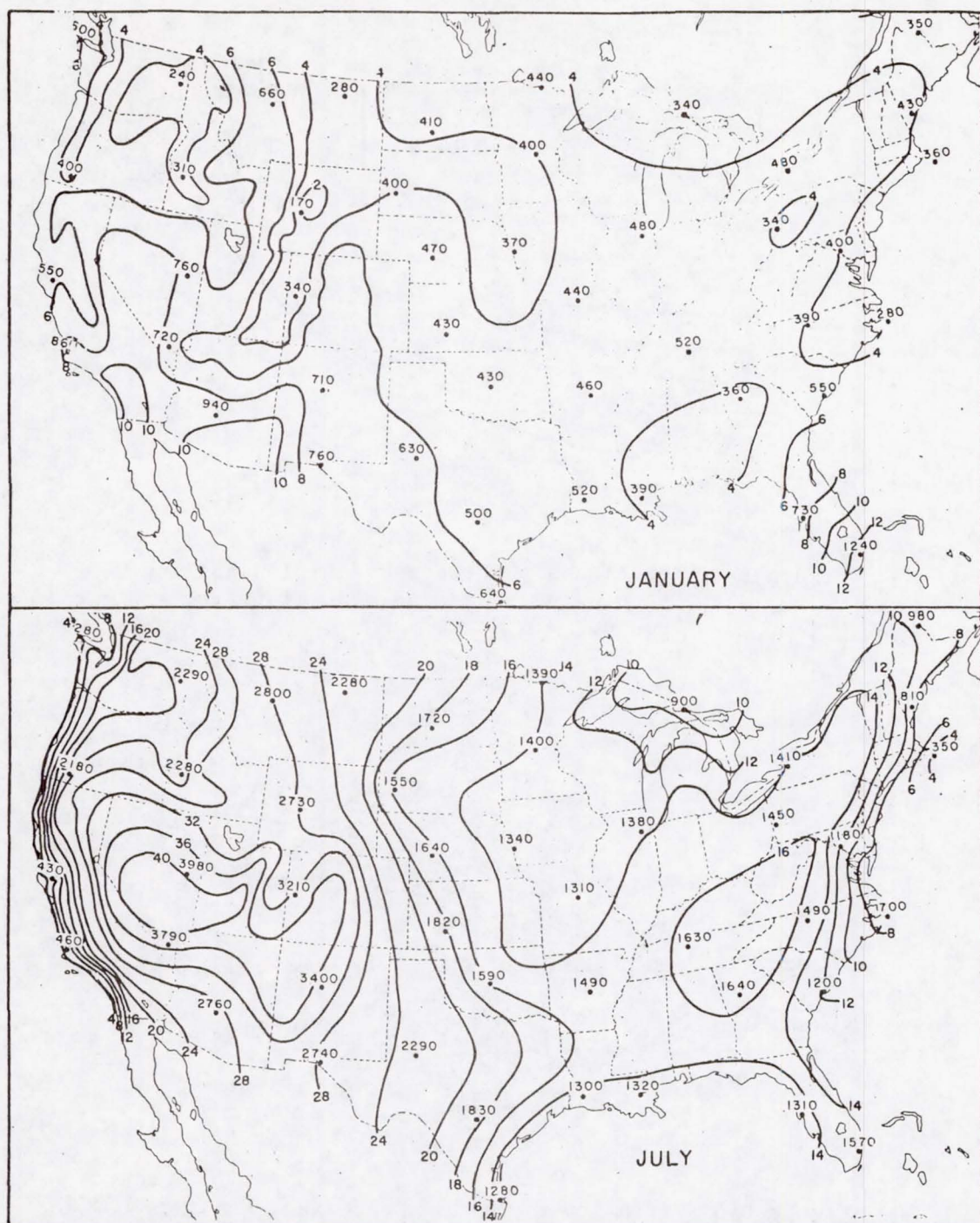


Figure D-6: Mixing Depth Contour Map of U.S.
for Two Months [D.12]

It is clear from the above description of the air traffic weather classification that it has very little correlation with the atmospheric stability classification. Only qualitative comparisons can be made. For example, if an overcast condition exists with poor visibility (IFR), the atmospheric stability can be assumed to be neutral (D). IFR conditions due to fog may indicate stable atmosphere (F or G). Conditions of heavy rain or thunder storms are difficult to classify within the Pasquill stability classification.

D.4.2 Dispersion Models

D.4.2.1 Dispersion of Neutrally Buoyant Gases and Particles

The dispersion of pollutants by the turbulence in the atmosphere is an extremely complex phenomenon which depends not only on the characteristics of the atmosphere and the wind conditions but also on the dispersing pollutant as well. Almost all of the dispersion analyses neglect, to a large extent, the pollutant particle size effects on dispersion and treat the particles as parcels of air (the notable exceptions being settling by gravity and washout by precipitation: see discussions below). Several types of neutral buoyancy dispersion theories have been propounded and discussed in the literature. These are reviewed in detail by Slade [D.12]. Basically, there are two main dispersion models. The first, called the "K theory" uses an essentially Fickian diffusion equation to describe the turbulent diffusion in the atmosphere. A turbulent eddy diffusion coefficient is used which varies with height above ground and accounts for surface roughness (for details see page 82 of Slade [D.12]). The second and perhaps a more extensively used model is the Gaussian dispersion model.

The basic characteristics of Gaussian dispersion model is that the time averaged spatial concentration distribution of a pollutant is given by a Gaussian profile. The variance of the Gaussian depends on the distance from the source, the direction in the atmosphere, the stability of the atmosphere and the duration of averaging. For example,

for the instantaneous ground level release of a given mass of material (M) the downwind concentration is given by

$$C(x, y, z, t) = \frac{M}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left\{ - \left[\frac{(x - \bar{u}t)^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2} \right] \right\} \quad (1)$$

where x , y , z , are respectively the downwind, crosswind and vertical distances, $\bar{u}$ and t are the mean wind speed and time after release. σ_x , σ_y , σ_z are respectively the longitudinal, crosswind and vertical standard derivations of the Gaussian. The principal differences amongst submodels of the Gaussian type are in relating the above σ 's to meteorological conditions. For example, Sutton (see p. 87 of Slade [D.12]) uses the following form:

$$\sigma_y^2 = \bar{y}^2 = \frac{1}{2} C_y^2 (\bar{u}t)^{2-n} \quad (2)$$

$$C_y^2 = \frac{4\nu^n}{(1-n)(2-n) \bar{u}^n} \left(\frac{\overline{v'^2}}{\bar{u}^2} \right)^{1-n} \quad (3)$$

where C_y^2 is called the virtual diffusion coefficient, n is related to the power of wind speed variation with height, ν the kinematic viscosity of air, $\overline{v'^2}$ is the mean square horizontal velocity fluctuations (also the intensity of turbulence) and $\bar{u}$ is the mean wind speed. Others have used

$$\sigma_y = \sqrt{\frac{\overline{v'^2}}{\bar{u}}} x \quad (4)$$

Pasquill has correlated for 10 minutes averaging times σ_y and σ_z with downwind distance with atmospheric stability as a parameter (see Figures D-3a and D-3b). Since the standard deviation of the concentration profile depends on the "averaging time" and the sampling time, the following formula relates to the dispersion parameter values with averaging time:

$$\sigma(t) = \sigma(t_0) \left(t/t_0 \right)^{1/5} \quad (5)$$

Cramer [D.13] prefers the use of the following equation for determining σ_y

$$\sigma_y = \sigma_\theta x \quad (6)$$

where σ_θ is the standard deviation of the horizontal wind direction and x the downwind distance. There seems to be substantial justification for using the above relationship except under extremely stable weather condition. For a detailed discussion see Slade [D.12]. Slade also gives a table of relationship between Pasquill stability class and measured σ_θ . This is reproduced in Table D-3.

Because of the wide acceptance of Pasquill atmospheric categories (and their modifications) and because of the organization by NCC meteorological data collected all over U.S., using Pasquill categories [D.5]. Pasquill method of calculating dispersion of pollutants (using graphically tabulated σ_y and σ_z) will be used in this report for analyzing the carbon fiber dispersion. The Pasquill equations will be suitably modified to take into account the nature of carbon fibers.

TABLE D-3

Relationship Between Pasquill Stability Class
and Horizontal Wind Direction Standard
Deviation (σ_θ)

Stability Class	Description	σ_θ (degree)
A	Extremely unstable	25
B	Moderately unstable	20
C	Slightly unstable	15
D	Neutral	10
E	Slightly stable	5
F	Moderately stable	2.5

The general formulas for the evaluation of pollutant concentrations using the Gaussian models are given below (Slade [D.12], p.97).

For an instantaneous point source

$$C(x, y, z, t) = \frac{M}{(2\pi)^{3/2} \sigma_y^2 \sigma_z} \exp \left\{ -\frac{(x - \bar{u}t)^2}{2\sigma_y^2} \right\} \exp \left\{ -\frac{y^2}{2\sigma_y^2} \right\} \left[\exp \left\{ -\frac{(z-h)^2}{2\sigma_z^2} \right\} + \exp \left\{ -\frac{(z+h)^2}{2\sigma_z^2} \right\} \right] \quad (7)$$

and for a continuous point source

$$C(x, y, z) = \frac{\dot{M}}{2\pi \sigma_y \sigma_z \bar{u}} \exp \left(-\frac{y^2}{2\sigma_y^2} \right) \left[\exp \left\{ -\frac{(z-h)^2}{2\sigma_z^2} \right\} + \exp \left\{ -\frac{(z+h)^2}{2\sigma_z^2} \right\} \right] \quad (8)$$

Where M and $\dot{M}$ are respectively the total mass released and the rate of mass release. The height of the source is represented by h , the equations give the time averaged value for the downwind concentration C .

D.4.2.2 Dispersion of Particles with Appreciable Settling

The airborne cloud of particles whose density is larger than that of air tend to settle to the ground. The rate of settling depends on the particle density, particle size, geometry and on wind and turbulent conditions. In the absence of any external disturbances, particles settle out at their terminal velocities (V_s). During the settling process the particles are subjected to the turbulent velocity fluctuations in the atmosphere and are, therefore, dispersed. It is also known that particles settling in a turbulent field have effective settling velocities (V_d) which are higher than V_s . A comprehensive discussion on this turbulence induced enhancement of settling velocity is given by Pasquill [D.5]. This effect of enhancement of V_d by turbulence is more pronounced for small particles (with V_s less than about 1 cm/s).

Because of the particle settling, the total mass of particles in the dispersing cloud is reduced from section to section downwind. There are essentially two methods given in the literature for analyzing dispersion with mass loss due to settling.

The first model is called the cloud depletion model. This model is applicable to cases where the depletion rate is large due to either the particle terminal velocities being high or that the ground concentration are large or both. Such a situation can be visualized for carbon fiber releases close to the ground; in which case the ground concentrations are high.

For a perfectly reflecting ground, the concentration of the particles at any distance x from an instantaneous source is given by (Slade, [D.12], p.204):

$$C(x,y,0) = \frac{2M_x}{(2\pi)^{3/2} \sigma_y^2 \sigma_z} \exp \left\{ - \left[\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2} \right] \right\} \quad (9)$$

where M_x is the mass of particles in the dispersing system when the center of cloud is at distance x from the source, h is the height of the source above ground. Other symbols have usual meanings. The mass in the dispersing cloud at any distance x is calculated by

$$\frac{M_x}{M_0} = \left[\exp \left\{ - \int_0^x \frac{dx}{\sigma_z(x) \exp(h^2/2\sigma_z^2)} \right\} \right]^{-\sqrt{\frac{2}{\pi}} \frac{V_d}{u}} = p \quad (10a)$$

where M_0 is the mass released and V_d is the effective velocity of settling of the particles.

The depletion rate (i.e., the rate of removal of mass from the cloud per unit time and unit area of the ground) is given by

$$\omega(x,y) = V_d C(x,y,0) \quad (11)$$

In Equation 10 to obtain the variation of the depletion factor p as a function of x , the variation of σ_z with x has to be known in addition to V_d and $\bar{u}$. σ_z varies with x in different ways for different atmospheric stability conditions. Slade ([D.12], p.205) has plotted the variation of p with x for different atmospheric conditions, for specific values of wind speed ($\bar{u} = 1$ m/s) and settling velocity ($V_d = 1$ cm/s). These are shown in figures D-7a through D-7f. From Equation 10 it can be shown easily that the depletion factor for any other wind speed, settling velocity combination can be obtained using the formula:

$$p(\bar{u}_2, V_{d,2}) = \left[p(\bar{u}_1, V_{d,1}) \right]^{\frac{\bar{u}_1 V_{d,2}}{\bar{u}_2 V_{d,1}}} \quad (10b)$$

For the calculations indicated in this report, Slade's curves (Figures D-7a through D-7f) are used to obtain p_1 and p_2 ; the depletion factors for the situations under this study are obtained using Equation 10b.

Tilted Plume Model

Another model that is commonly used in describing the dispersion of a plume (or a puff) containing particles heavier than air is the Tilted Plume Model. This model as discussed by Pasquill ([D.5], p. 255), is shown schematically in Figure D-8. The plume is released at a certain height in a wind of speed $\bar{u}$. The particles settle at an effective settling speed of V_d . The plume is, therefore, tilted with respect to the horizontal. Pasquill's treatment of the dispersion by tilted plume is equivalent to a Gaussian concentration distribution sinking into the ground at velocity V_d . The only mass that is left in the dispersing system is the mass in the Gaussian above the ground. The Gaussian distribution itself is not altered by the settling. The ground is, therefore, a perfect one-way sieve. While this is a representation of a perfect absorber, the ground is not a "sink;" in the latter case the "concentration" of particles at ground level should be zero.

The rate of mass removal from the tilted plume at any downwind position is given by (Pasquill, [D.5], p. 255).

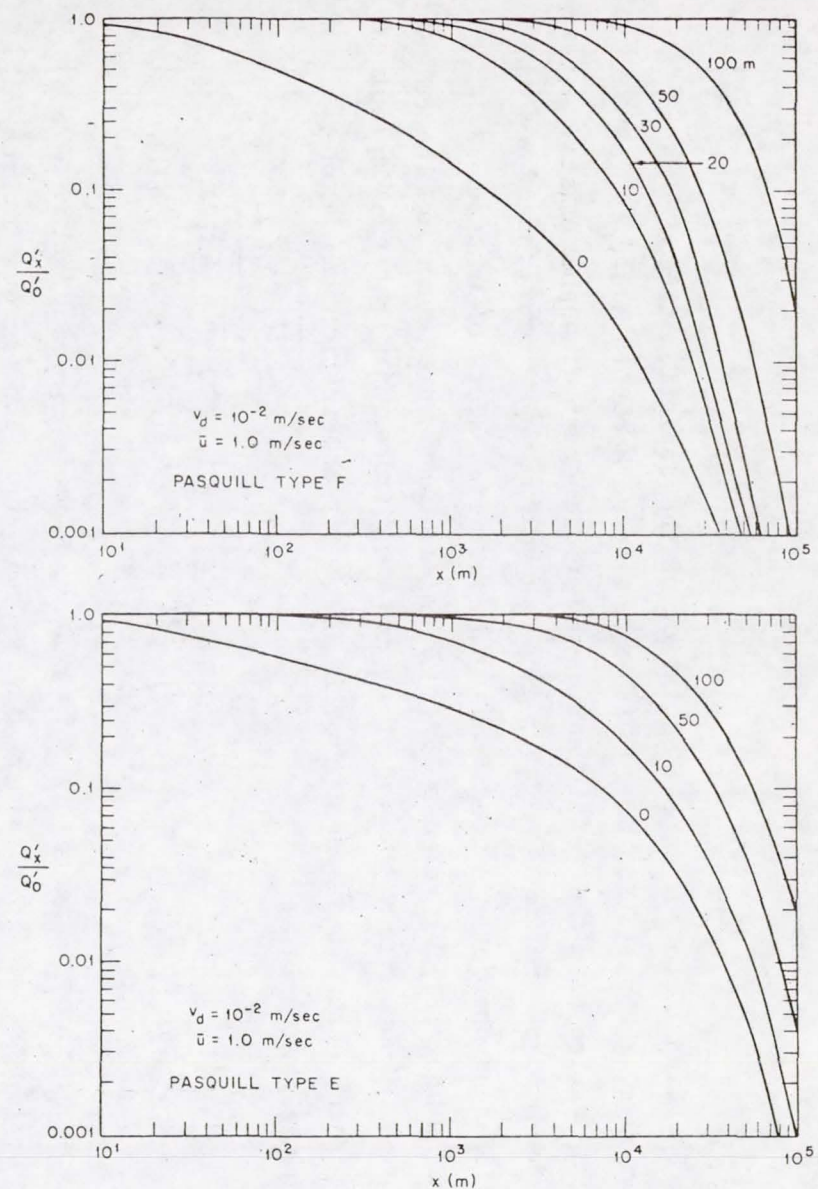
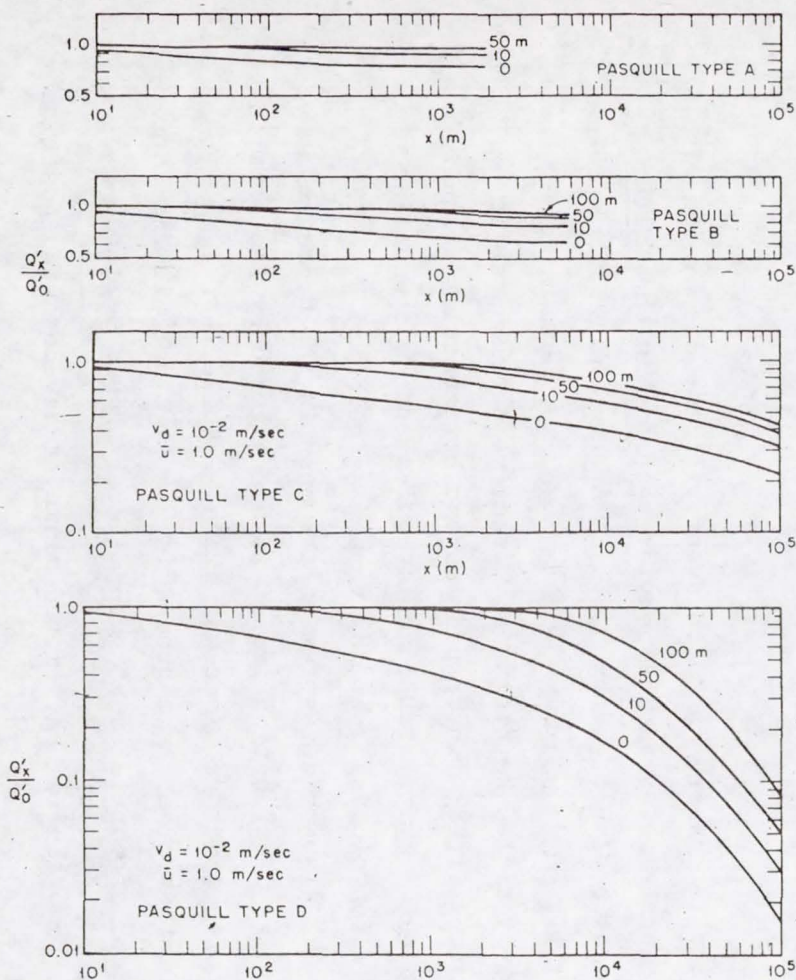


Figure D-7: Source-Depletion Fraction, p , for a wind speed $\bar{u}$, of 1.0 m/sec, a Deposition Velocity, V_d , of 10^{-2} m/sec, for source heights from 0 to 100 m above the Ground and for Various Stability Categories. [Slade (1968)]

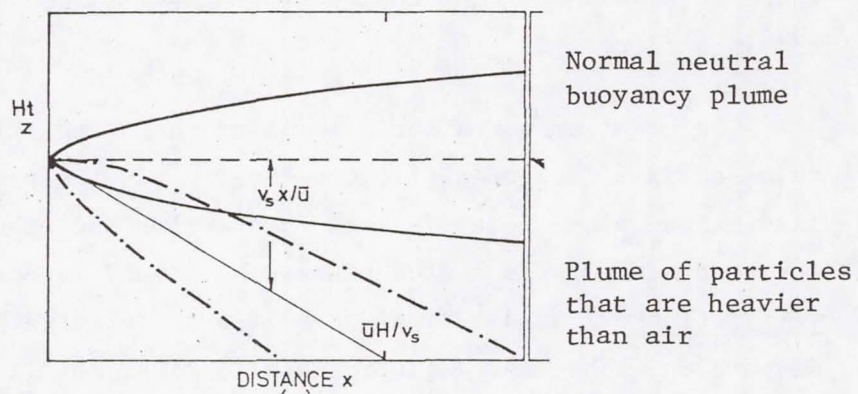


Figure D-8: Schematic Representation of the Tilted Plume for the Dispersion of Particles that Settle Out.

$$\dot{m}_{\text{Settling}} = \frac{V_d \dot{M}}{2\pi \bar{u} \sigma_y \sigma_z} e^{-y^2/2\sigma_y^2} e^{-\left[(H - V_d x/\bar{u})^2/2\sigma_z^2\right]} \quad (12)$$

where it is assumed that the particles setting on the ground are retained there.

The model proposed for describing the carbon fiber dispersion released in a fire of sufficient duration is the plume model. A modified tilted plume model is used to describe the fiber dispersion. In our treatment of the tilted plume, the ground is assumed to be a perfect reflector for determining the fiber concentrations in air during dispersion. The mass depletion due to fiber settling is taken into account in a way similar to that discussed by Slade [D.12], and as described in the earlier section on cloud depletion.

D.4.2.3 Dispersion and Removal of Particles by Rain and Other Precipitation

Rain and snow tend to cleanse the atmosphere of airborne pollutants. If the pollutants are particles or aerosols they are removed essentially by mechanical scrubbing action of the rain drops or snow flakes. Soluble gases are removed by dissolution in water. Slade [1968] has reviewed comprehensively the theory of wash out by rain and scavenging by snow. It is seen that wash out by rain of particles is measured by a coefficient (Λ) which has the units of inverse time. The coefficient represents the efficiency of removal of particles from the atmosphere. The wash out coefficient depends on particle size, density, rain drop diameter and rain fall rate (for more details see Slade, [D.12]).

The effect of rain is to remove mass from the dispersing (particle) system. If C_0 is the concentration (mass per unit volume of space) of particles at the beginning of rain, then the concentration at any time t is given by

$$C = C_0 e^{-\Lambda t} \quad (13)$$

The rate of removal of mass per unit area normal to the direction of motion of rain drops is given by

$$\dot{m}_{\text{removal}}'' = C\Delta \quad (14)$$

The wash out coefficient can vary from place to place depending on the characteristics of rain showers over a wide area. If a dispersing plume containing carbon fibers encounters rain showers it is very likely that a significant fraction of the fibers in the plume will be scavenged; depending on the rain characteristics and the downwind extent of area that is exposed to rain showers. From the analysis given by Slade [D.12], the following can be shown:

$$M(L) = M_0 e^{-(\Lambda L/\bar{u})} \quad (15)$$

where M_0 is the mass of fibers in the dispersing cloud before entering rain showers, $M(L)$ is the same mass after passing through rain cloud. The downwind extent of rain cloud is indicated by L .

The above ideas of wash out by rain were incorporated into the model developed for CF dispersion analysis.

D.4.3 Plume Rise Models

When a large fire occurs in the open, the hot combustion gases rise into the atmosphere in the form of a plume. The phenomenon of plume rise in the atmosphere has been a subject matter of extensive theoretical and observational studies. Briggs [D.1] has given an extensive review of the literature concerning the behavior of smoke plumes, observational data and plume rise formulas available in the literature. Therefore, no in-depth review of plume behavior models will be given here. Only, the generally accepted formulas for plume rises under several atmospheric conditions will be reviewed.

For plume rise in neutral windy atmosphere (in which potential temperature gradient is constant with height) the buoyancy induced rise of the plume is not terminated at all. The rise height at any downwind distance is given by:

$$H_p = 1.8 \frac{F^{1/3} x^{2/3}}{\bar{u}} \quad (16)$$

where F is the source parameter related to the heat release rate by:

$$F = g Q_H / (\pi \rho_a c_a T_a) \quad (17)$$

where Q_H is the total convective upward heat flow rate per unit time from the source.

Briggs [D.1] has suggested that in neutral atmosphere the plume reaches a maximum height when the upward rise velocity of plume is some small fraction of vertical eddy velocities in the wind. Based on this, Briggs has indicated the use of following formula (in SI units)

$$x^* = 67.3 F^{2/5} \quad \text{for } H_p > 300 \text{ m} \quad (18)$$

$$x^* = 2.164 F^{2/5} H_p^{3/5} \quad \text{for } H_p < 300 \text{ m} \quad (19)$$

where x^* is the distance at which the plume reaches the ceiling height. The ceiling height is obtained by substituting x^* for x in plume rise Equation 16.

Because of lack of data and theory to characterise plume rise in unstable atmosphere, the formula for rise in neutral atmosphere is suggested for use in unstable atmosphere also.

For plume rise in stable atmosphere the following formula are generally used:

$$H_p = 2.9 \left(\frac{F}{\bar{u} s} \right)^{1/3} \quad \text{for wind speeds } > 4 \text{ m/s} \quad (20)$$

$$H_p = 5 \left(\frac{F^2}{s^3} \right)^{1/8} \quad \text{for wind speeds } < 2 \text{ m/s} \quad (21)$$

Where, $S = g/T_a \partial \theta / \partial z$ (22)

In the above equations S is the "atmospheric stability parameter" defined based on the potential temperature gradient in the atmosphere. There does not seem to be any quantitative relationship between S and the Pasquill atmospheric stability categories. Trethway [D.7] has used certain potential temperature gradient values. These are indicated in Table D-4.

TABLE D-4

Relationship Between Potential Temperature
Gradient and Pasquill Stability Class

Pasquill Atmospheric Category	Potential Temperature Gradient $\frac{\partial \theta}{\partial z}$ (K/m)	Atmospheric Stability Parameter [*] $S = \frac{g}{T} \left(\frac{\partial \theta}{\partial z} \right)$ (1/s ²)
A	} Negative. Exact values not available	Negative
B		
C		
D	0.005	1.701×10^{-4}
E	-	-
F -day	0.03	1.021×10^{-3}
F -night	0.07	2.382×10^{-3}

* A mean atmospheric temperature of 288 K is assumed.

D.5 NOMENCLATURE

<u>Symbol</u>	<u>Description</u>	<u>Equation</u>	<u>Units</u>
C	Concentration at a given point and time	(1)	kg/m^3
C_o	Concentration at the beginning of rain	(13)	kg/m^3
C_a	Specific heat of air	(17)	
C_y	Virtual diffusion coefficient	(2)	$(\text{m})^{n/2}$
D	Fiber exposure	(6.4)	Ps/m^3
D^*	Prescribed fiber exposure	(6.8)	Ps/m^3
D_{max}	Maximum fiber exposure	(6.7)	Ps/m^3
F	Buoyancy flux parameter	(16)	m^4/s^3
g	Acceleration due to gravity	(17)	m/s^2
h	Source height	(7)	m
H_m	Mixing depth	(6.22)	m
H_p	Maximum plume height	(6.12), (16)	m
L	Downwind extent of rain cloud	(15)	m
$\dot{m}_f$	Rate of burning of fuel		kg/s
$\dot{m}''_{\text{removal}}$	Rate of removal of mass	(14)	$\text{kg/m}^2 \text{ s}$
$\dot{m}_{\text{settling}}$	Rate of removal of mass	(12)	$\text{kg/m}^2 \text{ s}$
M	Total mass of fibers released	(1)	kg
$\dot{M}$	Rate of mass release	(8)	kg/s
M_o	Total mass released	(10)	kg
M_x	Mass in the dispersing system at x	(9)	kg
n	Sutton's parameter	(2)	
N (x)	Number of particles at x	(6.20)	
N_o	Total of particles released	(6.20)	
p(x)	Depletion function	(10)	
Q	Heat of combustion	(6.9)	J/kg
Q_H	Total heat release rate in fire	(17)	J/kg s
r	Stoichiometric air fuel ratio	(6.9)	
S	Atmospheric stability parameter	(22)	
t	Time after release	(1)	s
t_o	Averaging time	(5)	s

<u>Symbol</u>	<u>Description</u>	<u>Equation</u>	<u>Units</u>
T_a	Ambient temperature	(17)	$^{\circ}\text{K}$
$\bar{u}$	Mean velocity in x-direction	(1)	m/s
U_w	Wind velocity	(6.2)	m/s
v'	Deviation of velocity in y-direction	(2)	m/s
V_d	Terminal velocity	(10)	m/s
$W(x)$	Width of contour of exposure D^* at any x	(6.8)	m
x, y, z	Coordinate system	(1)	m
x^*	Location of maximum plume height	(6.13), (18)	m
x_c	Location of the center of fiber cloud at time t	(6.2)	m
<u>GREEK</u>			
ΔT	Temperature difference between air temperature in plume		$^{\circ}\text{K}$
Δ	Wash out coefficient	(13)	s^{-1}
η	Fraction of combustion energy radiated		
ν	Kinematic viscosity	(2)	m^2/s
ρ	Gas density in plume		kg/m^3
ρ_a	Ambient density	(17)	kg/m^3
$\frac{\partial \theta}{\partial z}$	Potential temperature gradient		$^{\circ}\text{K}/\text{m}$
$\sigma_x, \sigma_y, \sigma_z$	Standard deviation of the distribution of pollutant	(1)	m
σ_{θ}	Standard deviation of the lateral wind direction distribution	(6)	radians
ω	Depletion rate	(11)	$\text{kg}/\text{m}^2 \text{ s}$

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E: ANALYSIS OF TRANSFER FUNCTION PARAMETERS

E.1 FILTER EFFICIENCY EVALUATION

E.1.1 Introduction

Forced-air ventilation systems in buildings and other structures typically incorporate air filtration devices to reduce levels of atmospheric dust within incoming air supplies. The filters serve to minimize soiling of interior surfaces as well as to prevent components of HVAC systems from becoming clogged with dust.

A wide variety of air filter types are commercially available from numerous manufacturers. Each type, as well as particular brand of filter, has its own assigned efficiency for the capture of atmospheric dust. These efficiencies are determined by a standard testing method, and are referred to as "atmospheric dust spot" filter efficiencies. Virtually all manufacturers rate their filters by this test method. Similarly, virtually all guidebooks and design guides recommend filters on this basis for particular applications.

Dust spot efficiencies cannot be directly utilized in computations involving carbon fibers because the size and shape characteristics of carbon fibers differ significantly from those of atmospheric dust particles. In consequence, it is necessary to relate dust spot efficiencies to efficiencies actually expected for carbon fibers, using whatever data is at hand. This is the intent of the following analysis.

E.1.2 Dust Spot Efficiency Testing Methods

Atmospheric dust spot efficiency testing methods are intended to measure the ability of a filter to reduce soiling of fabrics and interior building surfaces due to common contaminants found in internal or external atmospheres. Early test methods were established by the American Filter Institute (AFI) and the National Bureau of Standards (NBS). In 1968 the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) unified the AFI and NBS methods into a single test procedure, and it is the ASHRAE method [10] which is widely used today.

The ASHRAE test duct utilizes air samplers placed both upstream and downstream of a test filter. These samplers draw air containing untreated atmospheric dust through special glass fiber filter papers in order to cause a discoloration effect which is quantified by a light intensity meter. A mathematical formula then provides an average dust spot efficiency over the simulated life of the filter being tested.

E.1.3 Filter Efficiencies Desired

The dust spot efficiency of a filter provides a relative indication of the capability of that filter to capture atmospheric dust. As such, it is not appropriate for use in computations involving the effectiveness of a filter to capture particulate matter with specific size and shape characteristics.

In dealing with airborne dosages due to carbon fibers, we require filter efficiencies which indicate what fraction of the number of incoming fibers will be captured, i.e., we need an efficiency η such that:

$$C_I = (1 - \eta) C_O$$

where:

C_I is the carbon fiber concentration in air leaving an air filter;

η is the carbon fiber efficiency of that filter; and

C_O is the concentration of carbon fibers in air entering the filter.

E.1.4 Methodology

From a number of filter manufacturers and literature sources, we accumulated particle size versus efficiency data for typical filters with known dust spot filter efficiencies. Given the size and shape characteristics of carbon fibers, these allowed us to roughly bound our desired answers.

Limited experimental studies dealing with the carbon fiber efficiency of certain air filters allowed further refinement of some estimates. Unfortunately, the nature of the experiments severely limited their usefulness for this purpose.

Finally, we interviewed the research director of a major air filter manufacturer to validate and supplement our conclusions.

E.1.5 Uncertainties and Assumptions

We know that the diameter of carbon fibers range from 7.0 to 7.5 microns for aircraft applications. As to the length distribution of fibers which may be released from potential incidents involving aircraft, experiments cited in Section 2.2 of this report indicate lengths of 1 to 10 mm. for single fibers.

To the best of our knowledge, it is not possible to define the minimum length of fiber which may cause adverse effects in electronic equipment, since clumps of short fibers can conceivably have the same effect as one long fiber. Nevertheless, since such a minimum is necessary to the analysis, we conservatively assumed that the shortest fiber length of interest is approximately 100 microns, and that the longest length is on the order of 3 to 6 mm (3,000 to 6,000 microns). For each of a number of dust spot efficiencies, we therefore estimated a range of carbon fiber filter efficiencies which encompasses the range of fiber lengths.

We report elsewhere in this report that many filter installations allow bypass of contaminated air volumes around filters. We have accounted for such possibilities elsewhere, and here, assume that we are dealing with perfectly mounted filters under laboratory conditions.

E.1.6 Data Summary and Analysis

Table 1 summarizes the pertinent data accumulated. References 1 to 4 are air filter manufacturer product bulletins; 5 to 7 are papers in the literature; 8 is the opinion of the research director for a major air filter manufacturer; and 9 refers to the results of government sponsored experimental studies.

The data for 80 percent and higher efficiency filters are consistent and sufficient to conclude that no carbon fibers of significant length can penetrate such filters. Although a vague possibility exists that a

TABLE E-1
PARTICLE SIZE VERSUS FILTER EFFICIENCY

Particle Size vs. Efficiency Data			
Dust Spot Efficiency	Reference	Diameter (μm)	Filter Efficiency (%)
90 to 97%	4	> 5	100
	5	> 5	100
	6	> 5	100
	1	7	99.3 to 99.6
	3	7	99.92
	1	10	99.4 to 99.6
	3	20	99.96
	3	70	99.97
	8	CF*	100
80 - 85%	6	> 5	100
	4	> 6	100
	3	7	99.8
	1	7 to 10	99.2 to 99.3
	3	20	99.93
	3	70	99.96
	8	CF*	100
50 - 60%	4	7	82 to 85
	5	7.5 to 10	88
	1	7	98.1 to 99.2
	3	7	99.73
	1	10	98.5 to 99.3
	5	> 20	100
	3	20	99.91
	4	30	100
	3	70	99.95
	8	CF*	100
30 - 35%	2	7	92 to 93
	3	7	96 to 97
	4	7	82 to 85
	2	10	98 to 99
	3	20	98.8
	4	55	97 to 98
	3	70	99.94
	8	CF*	99.5 or better
20 to 25%	2	7	85 to 92
	2	10	92 to 97
	9	?	99.94

Particle Size vs. Efficiency Data

Dust Spot Efficiency	Reference	Diameter (μ m)	Filter Efficiency (%)
10 - 15%	6	7.5	40 } "typical" furnace
	6	20	86 } filter
	7	16 to 22	45 to 56 (1" furnace filter)
	7	16 to 22	62 to 75 (2" furnace filter)
	9	CF (L = 12 mm)	98.08 (1" furnace filter)
	8	CF*	"high 90's" (roll filter)
	8	CF*	"better than 90" (1" furnace filter)
<10	9	CF (L = 6 mm)	92.17

* For 100 micron fiber length (extrapolated data)

few fibers may penetrate filters by "worming" through with a pointed end in front, we do not believe this phenomena is very credible with the high density types of filters of concern.

At a 50 to 60 percent efficiency level, we again have strong evidence that no carbon fibers can penetrate filters under laboratory conditions. Again, we note but discount the possibility of "worm-through."

At a 30 to 35 percent level, a filter research director we contacted stated it would be fully conservative to estimate 0.5 percent or less penetration for 100 micron length fibers. This assessment appears to be reasonable, and suggests an efficiency range of 99.5 to 100 percent for the fiber lengths of concern.

Backtracking a bit, we now address 40 to 45 percent dust spot efficiencies, a range for which we were unable to obtain sufficient data to present. By considering our conclusions for other dust spot efficiencies, we estimate a carbon fiber efficiency range of 99.75 to 100 percent.

At lesser dust spot efficiencies, it becomes more difficult to estimate filter efficiencies for carbon fibers. Those few experimental data points which exist are for fiber lengths so long that even the crudest of filters capture high percentages. These are useful for estimating upper bounds, but not for lower ones.

One set of experiments involved a one-inch polyester pad with a dust spot efficiency on the order of 20 percent or less. This filter demonstrated 0.06 percent average penetration by carbon fibers of significant length. We can safely assume an upper bound of 99.9 percent efficiency for such a filter. For a lower bound, we can only crudely estimate an efficiency of 95 percent.

For a typical furnace filter of one-inch depth, experimentation has provided a 98.1 percent efficiency for carbon fibers of 12 mm length (the shortest length tested). This data point, therefore, provides an upper bound for an efficiency range. For estimation of a lower bound, we simply

have the opinion of the research director that better than 90 percent of fibers of 100 micron length will be captured. Without firmer data, we therefore choose a lower bound of 90 percent, and apply the resulting range to furnace filters (spun glass) of two-inch depth also.

E.1.7 Summary of Results

With full knowledge of the shortcomings of this analysis, we conclude the following relationships between atmospheric dust spot efficiencies and ideal expected efficiencies for carbon fibers of a variety of pertinent lengths.

<u>Dust Spot Efficiency</u>	<u>Fractional CF Efficiency (η)</u>
50 to 100%	1.00
40 to 45%	.9975 to 1.00
30 to 35%	.995 to 1.00
20 to 25%	.95 to .999
10 to 15%	.90 to .98

We have confidence that filters rated at 50 percent or above on the dust spot efficiency basis will capture all carbon fibers of greater than 100 micron length under laboratory conditions. In consequence, we simply present a single efficiency of exactly one for these types.

The lower bounds of the efficiency ranges for 30 to 35 and 40 to 45 percent filters are somewhat arbitrarily chosen. We have significant confidence that they are conservative for fiber lengths on the order of 1 mm and above. We are not quite so certain of their validity for shorter lengths, and can only intuitively consider them conservative. The upper bounds presented are completely plausible, and do not require comment.

The upper bounds of ranges for 20 to 25 and 10 to 15 percent filters are essentially derived from experimental studies with long fibers. As such, they must be considered of acceptable accuracy at this time. The lower bounds, however, are crude estimates. While we intuitively believe them to be conservative, we must express some uncertainties.

E.1.8 Further Comments and Recommendations

A proper analysis of filter efficiencies for carbon fibers requires information not currently available. If the government decides to pursue this matter further, we recommend the following areas for research.

1. It is necessary to define the length distribution of fibers which may be released from incidents involving aircraft or other structures containing composite materials.
2. A number of representative filters for each of the dust spot efficiency ranges must be tested with carbon fibers of a number of lengths. The goal of this effort will be sufficient data to compute overall average filter efficiencies which reflect the expected fiber length distributions determined above.

E.2 INFILTRATION RATES

E.2.1 Introduction

According to Reference 10, infiltration is defined as the air leakage through cracks and interstices, around windows and doors, and through floors and walls of a building. It occurs to some extent in any type of building from a low one-story house or commercial building to a multi-story skyscraper. The specific magnitude of the phenomenon for any particular building, however, is a strong function of the type of construction; the wind and temperature difference forces which characterize the building and its locale; quality of workmanship; and the condition of the building. In consequence, infiltration is a dynamic phenomenon involving daily as well as seasonal variations.

One of two available methods is usually utilized by designers to estimate the rate of infiltration into various types of buildings. The crudest of these is the "air change method" and simply involves the use of "typical" air change rates which have been experimentally derived or otherwise found to be generally adequate for design purposes through long-term experience.

The second method is known as the "crack method" and is significantly more sophisticated. Utilizing various computational procedures, it attempts to allow consideration of external/internal pressure variations due to wind and temperature forces expected. Additionally, it accounts for the specific number, size, and type of all windows, doors, and walls on the exterior of the building, and other factors as they might influence the infiltration rate. Both methods are fully described in Reference 10 and elsewhere.

Application of the crack method to the large numbers of buildings of interest to this study, and/or the experimental determination of infiltration rates on a case-by-case basis was obviously not feasible. In consequence, the

following discussion attempts to assign ranges of air change rates to general categories of buildings by review of experimentally derived rates found in the literature for representative construction.

E.2.2 Residences

According to the ASHRAE Handbook of Fundamentals [10], the data presented in Table E-2 "may be used with reasonable precision for residences, and are the requirements for each room." It is common practice to assume that the total infiltration allowance for the residence is equal to the sum of the infiltration allowances of the individual rooms. Some engineers, however, assume that whatever air enters on the windward side generally leaves on the leeward side, and that the infiltration requirements do not simultaneously exist on all sides or in all rooms. Thus, they utilize one-half the sum of the infiltration allowance for the entire building.

For one estimate of total infiltration rates in residences, under average conditions, one can select a range of 1.0 to 1.5 air changes per hour by inspection of Table E-2. The only assumptions necessary are that

- 1) entrance halls usually constitute a small fraction of the building volume;
- 2) that rooms with windows or exterior doors on three sides are rare; and
- 3) that large rooms with no windows or exterior doors in residences are also rare.

Coblentz and Achenbach reported upon an experimental study to measure air infiltration in ten electrically-heated houses in 1963. [11] The houses chosen were of a wide variety of designs and construction materials to provide what was hoped to be a representative sample of residential construction. Under a wide variety of wind and temperature conditions, they measured infiltration rates ranging from 0.23 to 1.14 air changes per hour, with an average

TABLE E-2

INFILTRATION IN RESIDENCES

<u>Kind of Room or Building</u>	<u>ACPH</u>
No windows or exterior doors	0.5
Windows or exterior doors present	
- on one side	1.0
- on two sides	1.5
- on three sides	2.0
Entrance halls	2.0

Notes:

ACPH = air changes per hour due to infiltration

For rooms with weatherstripped windows or with storm sash,
use 2/3 these values.

rate of 0.64 for 30 tests. When all results were mathematically adjusted to a uniform indoor-outdoor temperature difference of 40°F, and a uniform wind velocity of 10 mph, the range became 0.23 to 1.24 air changes per hour with the same average of 0.64. These results were said to agree well with the data given by ASHRAE, although inconsistencies were found for individual residences. Additionally, no significant correlation was found between the infiltration rate and age of the house or type of wall or foundation construction, although it was observed that 2-story buildings appeared generally to have higher infiltration rates than 1-story buildings (an average of 0.76 versus an average of 0.54).

Ambrose [12] reported in 1975 that 0.5 to 0.75 air changes per hour are often assumed for infiltration rates in electric heated residences with full insulation, double windows, and double doors. He suggests, additionally, that the rate can be "much greater" when fossil fuel heating systems are utilized and air for combustion and flue drafts exhausts are involved.

Tamura [13] studied six single-family residences constructed during the early nineteen-fifties. Two were identical in construction, while four were somewhat different in numbers of stories and/or exterior sidings. All were of insulated wood-frame construction and were heated by forced warm-air heating systems with high-pressure gun-type oil burners. The nature of his experiments do not allow conclusions as to typical naturally occurring infiltration rates, because he literally forced leakage into the homes with a 3000-cfm capacity fan (to obtain a uniform 0.30 in of water indoor/outdoor pressure difference). Nevertheless, certain of his conclusions are enlightening. More specifically, it was found that:

- Leakage values of windows and doors with storm units contribute from 15 to 24 percent of overall leakage values, with the remainder of flow through ceilings (8 -67%) and walls (15-77%).
- Storm units reduced leakage through double-hung windows by 26 - 44%, and 32 - 42 % through wood doors. Reductions of 30 - 71% were observed for wood horizontal sliding windows.

In previous work, [14] Tamura studied two of the six homes cited above. Winter measurements indicated total air change rates of 0.20 to 0.60, with a large fraction due to furnace operation. Summer measurements indicated that each mph of wind (up to 8 mph) increased the infiltration rate by 0.017 to 0.02 air changes per hour. At a wind velocity of 8 mph, therefore, one can estimate rates of 0.136 to 0.16 due solely to wind effects.

Bliss [15] reports that Federal Housing Administration standards specify a maximum air infiltration rate of 1.0 air changes per hour. Heldenbrand [16] in a National Bureau of Standards publication dealing with design criteria for new buildings, states that leakage ideally should not exceed 0.7 air changes per hour for one- and two-family dwellings and 0.5 air changes for all other buildings and mobile homes.

Hung and Burch [17] investigated infiltration into a four-bedroom townhouse placed inside a high-bay environmental chamber where wind velocity was not a factor. They generally found that the infiltration rate was directly proportional to the inside/outside temperature difference, and ranged from 0.11 to 0.82 air changes per hour when the temperature difference ranged from 9.6°F to 52.3°F.

Behnfleth et al. [18] studied infiltration in two dwellings at the University of Illinois. Rates varied from 0.16 to 0.43 changes per hour for one house (with gas-fired forced air furnace) under a variety of operating conditions, and from 0.26 to 0.80 for the other (with hot water heating system using gas). It was found that an increase in wind velocity of one mph was equivalent to an increase of indoor-outdoor temperature difference of 2 to 4°F in its effect on the infiltration rate.

Conclusions

In gross terms, all data cited above are consistent in suggesting that infiltration rates for residences are minimally on the order of 0.2 to 0.4 air changes per hour, average somewhere in the range of 0.4 to 0.7, and rarely exceed 1.25, when all windows and doors are closed. In consequence, a range of 0.2 to 1.5 air changes per hour is chosen as representative for residences and similar structures under a wide variety of conditions.

E.2.3 Other Buildings

Although many studies have attempted to characterize total infiltration rates in residences, apparently few have involved other types of buildings. ASHRAE [10] notes that, except for vestibules and reception halls, the air change method is not accurate for industrial or commercial buildings due to wide variations in the type and amount of fenestration, the principal leakage source in such buildings. Nevertheless, one can obtain an understanding of the ranges involved by reviewing available data.

One set of experiments cited by ASHRAE involved six office buildings with sealed windows and exterior spandrel panels of either concrete or aluminum. Measured infiltration rates ranged from 0.33 to 1.0 air changes per hour at

a pressure differential of 0.3 in of water. Additionally, this source notes that experiments in a nine-story building with masonry walls and operable aluminum sash windows indicated that windows and doors contribute approximately 25 percent of the total leakage. The remaining 75 percent was attributed to leakage through the masonry walls.

Lagus [19] cites a study [20] which found infiltration rates ranging from 0.36 to 0.92 air changes per hour in a nine-story building, depending on whether outside air vents were open or closed.

Conclusions

The sparse data available suggest that the rate of infiltration into any type of public or commercial building is comparable to rates determined for residences, and indeed, may be somewhat less on the average due to the common use of sealed windows in modern construction. In consequence, an infiltration rate range of 0.2 to 1.0 air changes per hour appears to be appropriate for general use in computations. Exceptions will involve occupancies such as computer rooms and surgical suites where special care is taken to reduce infiltration.

E.3 DERIVATION OF BUILDING PENETRATION MODEL

E.3.1 Introduction

This section presents the derivation of the building penetration model utilized in the risk analysis. The derivation proceeds in three major steps. First, we consider concentration build-up in internal areas during the time period the external cloud of contaminants envelops the building. This is followed by derivation of an equation representing the purging process which takes place after the tail-end of the cloud has passed. Finally, we integrate the resulting equations for concentration as a function of time over appropriate time spans, combine the results, and present our model equations in final form.

E.3.2 Nomenclature

Q_{MU} = mechanically provided fresh air inlet rate

Q_R = air recirculation rate

Q_N = natural ventilation rate

Q_I = infiltration rate

$\bar{C}_O$ = average concentration of fibers in passing cloud

C = concentration at any time t

C_1 = concentration at time t_1 where t_1 is the instant the leading edge of the cloud reaches the building

C_2 = concentration time t_2 where t_2 is any time subsequent to t_1 while the cloud envelops the building

C_2' = concentration at time t_2' where t_2' is the instant the tail-end of the cloud passes the building

C_3 = concentration at time t_3 where t_3 is any time subsequent to t_2'

η_F = overall efficiency of all air filter banks for carbon fibers

η_I = crack capture efficiency, i.e., efficiency of building materials to capture fibers in infiltrating air volumes

V = volume of affected internal space

V_S = settling velocity of carbon fibers in still air

A = exposed room surface area

H = ceiling height of affected space

E = internal exposure to airborne carbon fibers

Initially, we utilize airflow rates in any units of volume per unit time. Near the end of our analysis, we redefine these units as air changes per hour. Concentrations are expressed in fibers per unit volume, while most other parameters can be in any consistent units of time, velocity, volume, or length. The filter and crack capture efficiencies are dimensionless fractions such that an efficiency of 0.9 indicates that 90 percent of individual fibers will be removed from consideration.

E.3.3 Build-up Equation

Accumulation rate = Inlet rate - Outlet Rate

$$V \frac{dc}{dt} = (1 - \eta_F) \bar{C}_O Q_{MU} + (\text{from mechanical fresh air supply})$$

$$(1 - \eta_I) \bar{C}_O Q_I + (\text{from infiltration})$$

$$\bar{C}_O Q_N + (\text{from natural ventilation})$$

$$(1 - \eta_F) C Q_R - (\text{from recirculated air supplies})$$

$$C Q_{MU} - (\text{leaving in mechanical exhaust streams})$$

$$C Q_N - (\text{leaving in natural exhaust})$$

$CQ_I -$ (leaving in exfiltrating air)

$CQ_R -$ (leaving in exhaust to be recirculated)

CAV_S (leaving by deposition)

This is the basic equation for concentration build-up. Rearranging, we obtain:

$$\frac{1}{V} \int_{t_1}^t dt = \int_{C_1}^{C_2} \frac{dC}{A + BC}$$

where:

C_2 is the concentration at any time t ($t > t_1$)

C_1 is the initial concentration at t_1

$$A = \bar{C}_O [(1 - \eta_F)Q_{MU} + Q_N + (1 - \eta_I)Q_I]$$

$$B = -[Q_{MU} + Q_N + Q_I + \eta_F Q_R + AV_S]$$

Integrating, we obtain:

$$\frac{1}{V}(t - t_1) = \frac{1}{B} \left(\ln \frac{A + BC_2}{A + BC_1} \right)$$

at t_1 , $C_1 = 0.0$; solving for C_2 we obtain:

$$\ln \frac{A + BC_2}{A} = \frac{B}{V} (t - t_1)$$

$$\frac{A + BC_2}{A} = \exp \left(\frac{B}{V} (t - t_1) \right)$$

$$C_2 = \frac{A}{B} [\exp \left(\frac{B}{V} (t - t_1) \right) - 1]$$

$$C_2 = \frac{\bar{C}_o \left((1 - \eta_F)Q_{MU} + Q_N + (1 - \eta_I)Q_I \right)}{Q_{MU} + Q_N + Q_I + \eta_F Q_R + AV_S} \times [1 - \exp \left(\frac{Q_{MU} + Q_N + Q_I + \eta_F Q_R + AV_S}{-V} (t - t_1) \right)]$$

Although this equation for concentration build-up was independently derived, it was found to be essentially identical to an expression derived by Sutton and his co-authors. [E.21]

E.3.4 Purging Equation

At the point in time at which the tail-end of a cloud passes at building, contaminants will no longer enter internal spaces within fresh air supplies. These clean air supplies along with other phenomena will eventually purge internal air of all contaminants.

Purging rate = Inlet rate - Outlet rate

$$V \frac{dc}{dt} = (1 - \eta_F)CQ_R - \quad (\text{continuing inlet from recirculation system})$$

$$CQ_{MU} - \quad (\text{leaving in exhaust stream of rate } Q_{MU})$$

$$CQ_N - \quad (\text{leaving in exhaust stream of rate } Q_N)$$

$$CQ_I - \quad (\text{leaving in exfiltrating air volumes})$$

$$CQ_R - \quad (\text{leaving in air to be recirculated})$$

$$CAV_S - \quad (\text{leaving by deposition})$$

$$V \frac{dc}{dt} = -C [Q_{MU} + Q_N + Q_I + \eta_F Q_R + AV_S]$$

$$\int_{C_2'}^{C_3} \frac{dc}{c} = \int_{t_2'}^{t_3} \frac{-[Q_{MU} + Q_N + Q_I + \eta_F Q_R + AV_S]}{V} dt$$

$$\ln \left(\frac{C_3}{C_2'} \right) = \frac{-[Q_{MU} + Q_N + Q_I + \eta_F Q_R + AV_S]}{V} (t_3 - t_2')$$

where:

C_2' = concentration in room when tail-end of cloud passes building

t_2' = time associated with C_2'

C_3 = concentration at any time t_3 where $t_3 > t_2'$

The equation agrees in form with an expression derived on page 579 of reference 22.

E.3.5 Exposure Equation

To evaluate the airborne exposure expected internally, the two equations previously defined must be integrated over appropriate time spans and then summed.

$$\text{Let } A = \bar{C}_O Q_N + (1 - \eta_F) \bar{C}_O Q_{MU} + (1 - \eta_I) \bar{C}_O Q_I$$

$$B = Q_N + Q_{MU} + \eta_F Q_R + AV_S + Q_I$$

During build-up phase:

$$C_2 = \frac{A}{B} [1 - \exp(-\frac{B}{V} (t - t_1))]]$$

During purging:

$$C_3 = C_2^1 \exp [-\frac{B}{V} (t_3 - t_2^1)]$$

Therefore:

$$E = \text{exposure} = \int_{t_1}^{t_2^1} C_2 dt + \int_{t_2^1}^{\infty} C_3 dt_3$$

The first part expands to:

$$\int_{t_1}^{t_2^1} C_2 dt_2 = \int_{t_1}^{t_2^1} \frac{A}{B} dt + \int_{t_1}^{t_2^1} -\frac{A}{B} \exp(-\frac{B}{V} (t - t_1)) dt$$

For the second part, we need an expression for C_2^1 . From the build-up equation, at time = t_2^1 , we have:

$$C_2^1 = \frac{A}{B} [1 - \exp(-\frac{B}{V} (t_2^1 - t_1))]]$$

Therefore:

$$\begin{aligned} \int_{t_2^1}^{\infty} C_3 dt_3 &= \int_{t_2^1}^{\infty} C_2^1 \exp[-\frac{B}{V} (t_3 - t_2^1)] dt_3 = \int_{t_2^1}^{\infty} \frac{A}{B} \exp[-\frac{B}{V} (t_3 - t_2^1)] dt_3 + \\ &\int_{t_2^1}^{\infty} -\frac{A}{B} \exp(-\frac{B}{V} (t_2^1 - t_1)) \exp(-\frac{B}{V} (t_3 - t_2^1)) dt_3 \end{aligned}$$

Putting it together, the complete expression for exposure (E) is:

$$E = \int_{t_1}^{t_2} \frac{A}{B} dt + \int_{t_1}^{t_2} -\frac{A}{B} \exp \left(-\frac{B}{V} (t - t_1) \right) dt + \int_{t_2}^{\infty} \frac{A}{B} \exp \left(-\frac{B}{V} (t_3 - t_2^1) \right) dt_3 +$$

$$\int_{t_2}^{\infty} \left(\frac{A}{B} \right) \left(-\exp \left(-\frac{B}{V} (t_2^1 - t_1) \right) \right) \left(\exp \left(-\frac{B}{V} (t_3 - t_2^1) \right) \right) dt_3$$

There are four integrals:

$$\#1 \quad \int_{t_1}^{t_2} \frac{A}{B} dt = \frac{A}{B} (t_2^1 - t_1)$$

$$\#2 \quad \int_{t_1}^{t_2} -\frac{A}{B} \exp \left(-\frac{B}{V} (t - t_1) \right) dt = \left[-\frac{A}{B} \left(-\frac{V}{B} \right) \exp \left(-\frac{B}{V} (t - t_1) \right) = \right.$$

$$\left. \frac{AV}{B^2} \exp \left(-\frac{B}{V} (t_2^1 - t_1) \right) - \frac{AV}{B^2} \right]$$

$$\#3 \quad \int_{t_2}^{\infty} \frac{A}{B} \exp \left(-\frac{B}{V} (t_3 - t_2^1) \right) dt_3 = \left[-\frac{AV}{B^2} \exp \left(-\frac{B}{V} (t_3 - t_2^1) \right) = 0 \right.$$

$$\left. + \frac{AV}{B^2} \exp \left(-\frac{B}{V} (t_2^1 - t_1) \right) = \frac{AV}{B^2} \right]$$

$$\#4 \quad \int_{t_2}^{\infty} \left(-\frac{A}{B} \right) \left(\exp \left(-\frac{B}{V} (t_2^1 - t_1) \right) \right) \exp \left(-\frac{B}{V} (t_3 - t_2^1) \right) dt_3$$

Let $D = \exp \left(-\frac{B}{V} (t_2^1 - t_1) \right)$ for simplification

Then:

$$\int_{t_2}^{\infty} -\frac{AD}{B} \exp \left(-\frac{B}{V} (t_3 - t_2^1) \right) dt_3 = \left[-\frac{ADV}{B^2} \exp \left(-\frac{B}{V} (t_3 - t_2^1) \right) \right]_{t_2}^{\infty} =$$

$$0 - \frac{ADV}{B^2} \exp \left(-\frac{B}{V} (t_2^1 - t_2^1) \right) = -\frac{ADV}{B^2}$$

Assembling all parts:

$$E = \frac{A}{B} (t_2^1 - t_1) + \frac{AV}{B^2} \exp \left(-\frac{B}{V} (t_2^1 - t_1) \right) - \frac{AV}{B^2} + \frac{AV}{B^2} - \frac{AV}{B^2} \exp$$

$$\left(-\frac{B}{V} (t_2^1 - t_1) \right)$$

$$E = \frac{A}{B} (t_2^1 - t_1)$$

$$\text{Therefore internal exposure} = \frac{\bar{C}_o (Q_N + (1 - \eta_F)Q_{MU} + (1 - \eta_I)Q_I)}{Q_N + Q_{MU} + Q_I + \eta_F Q_R + AV_S} (t_2^1 - t_1)$$

All flow volume rates at this point are in units of unit volume per unit time. To convert these to the more common units of room volumes changed per unit time, we divide the numerator and the denominator by the room volume V , and redefine all ventilation rates as having units of air changes per hour (ACPH). Our only basic change in the equation involves the term AV_S . When we divide this term by V , we change the term to V_S/H , where H is the height of a room. Our final expression is then:

$$\text{Exposure} = \left[\frac{Q_N + (1 - \eta_F)Q_{MU} + (1 - \eta_I)Q_I}{Q_N + Q_{MU} + \eta_F Q_R + Q_I + \frac{V_S}{H}} \right] \bar{C}_o (t_2' - t_1)$$

Since the term $\bar{C}_o (t_2' - t_1)$ is by definition the external exposure of the building, we find that the external exposure multiplied by the term in brackets gives us the expected internal exposure. We therefore define the term in brackets as the airborne exposure transfer function (AETF) such that:

$$\text{AETF} = \left[\frac{Q_N + (1 - \eta_F)Q_{MU} + (1 - \eta_I)Q_I}{Q_N + Q_{MU} + \eta_F Q_R + Q_I + \frac{V_S}{H}} \right]$$

Internal Exposure = AETF x External Exposure

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F. DETAILS AND RESULTS OF BUILDING PENETRATION ANALYSIS

F.1 INTRODUCTION

The building penetration model described in the main body of this report was utilized to generate a range of airborne exposure transfer function (AETF) values for each occupancy type of concern to this study. Table 7-2 provides a summary of results.

This appendix provides details of the analysis on an occupancy by occupancy basis. As such, it is intended to convey the rationale behind the selection of specific values for each of the model parameters requiring specification.

F.2 DATA SOURCES

During the course of this study, we visited a wide range of buildings to gain insights and gather data concerning the penetration of carbon fibers into private, public, and commercial buildings. Appendix B of this report describes our field work strategy and the specific locations visited. Additionally, we conducted a literature survey on pertinent topics and interviewed numerous personnel by telephone to supplement our information.

F.3 GENERAL FORMAT AND APPROACH

F.3.1 Introduction

Each of the immediately following subsections discusses our general approach in attempting to estimate specific ranges of values for model parameters. Analogous subsections in Section F.4 discuss findings on a more specific basis for each occupancy type of concern.

F.3.2 Mechanical Air Change Rates

With few exceptions, the total ventilation rate in structures with forced air HVAC systems typically ranges from 2 to 15 air changes per hour (ACPH). Exceptions include occupancies with high heating or cooling loads, or installations which have unusual air quality requirements. Since the range cited is quite large, it is advantageous to define more limited ranges which more specifically typify practice in occupancy types of concern.

In visits to numerous facilities, we always attempted to define the actual ACPH provided by heating, ventilating, and air-conditioning (HVAC) systems. In some cases, where specific ventilation rates were critical, we were successful in this endeavor. Mostly, however, we found that personnel had no idea of specific rates, and could not easily lead us to those who were knowledgeable. This was especially true when the HVAC system was old but providing adequate temperature control, and/or the building had been leased from others.

The problems we would experience in defining typical rates for typical building types were predicted early in the study by a ventilation specialist for an agency which literally owns and operates a major international airport. This individual had been contacted for ventilation rates in various airport buildings after personnel who occupied the buildings had expressed ignorance on the subject. He strongly discouraged us from digging in his files for original building plans for the following reasons:

1. There was no consistency in ventilation practice from building to building. So long as building codes were satisfied, his agency was satisfied. Thus, the specific rates chosen were at or above those suggested in codes and various guidebooks, but were otherwise somewhat arbitrarily chosen by various HVAC system designers. There was no such thing as a single typical rate.
2. Many systems had been substantially modified by tenants over the years to meet specific needs. The original plans were quite often in error and had not been updated.

In consequence, to provide a range of rates which represent current practice in various classes of buildings, we often referred to guidebooks published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Being a prime source of information for designers, these provided rates which we assumed must be used in a large fraction of buildings. To supplement these data, we also conducted a literature survey to obtain descriptions of HVAC systems installed in various types of buildings. Together with our own observations, we were then in a position to define overall ACPH ranges which we felt were realistic.

Once we had estimated the range for the total ventilation rate, it was necessary to designate which fraction of this flow volume was comprised of outdoor air, and/or which fraction was recirculated from within the building. Again, we found variations, but not such a variety that we could not generalize for office-type buildings. Essentially, it was seen that 90 to 100 percent of the air was usually from outdoors when outdoor temperatures were within various specified limits. During hot weather, from two-thirds to 90 percent would be recirculated, while cold weather conditions called for 50 to 90 percent recirculation. Numerous exceptions were noted to these ranges, and most were individually accounted for in the computational process. Overall, however, we found that the specific fraction of air recirculated within the ranges specified did not have a highly significant effect on final results (a factor of 2 or 3 at the very most). Thus, we often present a single AETF value range in the following analysis which encompasses the individual ranges computed for hot, pleasant, and cold weather conditions.

F.3.3 Natural Ventilation Rate

Flow into open windows, doors and wall louvers due to wind can normally be estimated from the expression:

$$Q_N = \frac{E A_w V_w}{A_R H} \times 60$$

where:

Q_N = air flow into structure, ACPH (air changes per hour)

A_w = free area of inlet openings, square feet

V_w = wind velocity, fpm (= mph x 88)

E = effectiveness of openings (see below)

A_R = floor area, square feet

H = ceiling height, feet

An ASHRAE guidebook notes that E should be taken as 0.5 to 0.6 for perpendicular winds, and 0.25 to 0.35 for diagonal winds. Additionally, it notes that internal building resistance and differences between inlet and outlet opening areas can affect the total flow.

From inspection of various buildings and from our own experience, we estimated ranges of values for each of the parameters defined above. We then developed a simple computer program which would vary these parameters through their individual ranges to assess their effect upon airborne exposure transfer function (AETF) values for particular occupancy types of concern.

This analysis resulted in the finding that an open window or door at even low wind speeds can easily produce AETF values on the order of 0.4 to 0.6, regardless of the specific details of HVAC systems installed. Thus, although there are slight differences between the upper bounds of AETF value ranges for different occupancy types, most lie in or around the range 0.4 to 0.6 for open window conditions.

At the other extreme, we found that the slight opening of a single window or door in a relatively large building space resulted in an AETF value comparable to the upper bound of analogous ranges for closed window conditions. In direct consequence, the possibility of open doors or windows in a building suggests that the AETF value for that building can vary through a wide range if any doors or windows are open.

F.3.4 Infiltration Rate

With few exceptions, every building or other structure constructed with typical building materials allows inward leakage of air through cracks around windows and doors, and directly or indirectly through walls and ceilings. This unintentional and usually undesirable leakage is defined as the infiltration rate.

Appendix E.2 presents the results of an effort to define ranges of infiltration rates for various types of buildings. It concludes that a range of 0.2 to 1.5 ACPH encompasses conditions expected in residences and similarly constructed buildings, and that 0.2 to 1.0 ACPH is more appropriate for office buildings and the like. One of these ranges was generally applied to each occupancy type of concern in this analysis, except where other data suggested a need for modification.

F.3.5 Crack Capture Efficiency

If a contaminant in outdoor air is in the gaseous state, and is not reactive with building materials, it will freely penetrate nearby buildings along with infiltrating air volumes. Alternatively, if the contaminant is a relatively large particulate, some fraction or all will be captured by building materials along the tortuous route of entry to occupied spaces. It is clear that molecules of air can pass through microscopic crevices where large particles cannot.

To the best of our knowledge, there has been no experimental or theoretical work conducted which would allow one to definitively state what fraction of carbon fibers will succeed in penetrating a typical building within infiltrating air volumes. At one extreme, one might simply assume that no fibers will enter by this route. This is a plausible assumption and is one which can be supported on an intuitive, if not engineering, basis for many types of structures.

At the other extreme, one must note that infiltration rates include airflows through the sometimes wide cracks around doors and windows, through doors which are repeatedly opened and closed, and through various air vents, elevator shafts, normally closed wall louvers, etc. These latter leakage sources are obviously not as prone to provide a barrier to fiber entrance.

To resolve the issue, we defined a parameter which describes the fraction of infiltrating air which does not successfully convey carbon fibers into a structure. Similar to an air filter efficiency in form and use, it is referred to as the "crack capture efficiency." For each type of structure addressed in the following, we then estimated a range of expected values.

The upper bound of the range was taken to be 1.0 for most types of structures. That is, we assumed at one extreme that no fibers will penetrate the structure with infiltrating air. Where we determined that a particular type of structure is prone to have numerous relatively large openings to the outside, however, we appropriately modified this limit.

Definition of the lower bound for the range was the more difficult task. Our only information was that about 25 percent of infiltrating air enters through and around windows and doors, with the remainder attributable to leakage through walls and ceilings (see Appendix E dealing with infiltration rates). By noting that fibers cannot easily penetrate ceilings and walls, we simply assumed in most cases that no more than 25 percent of fibers in outdoor air can penetrate a structure within the air volumes of interest. Again, we modified the limit occasionally due to qualitative observations made during site visits.

The importance of these decisions varies with the particular penetration scenario being considered. Generally, the amount of fibers entering by this route was seen to be insignificant when:

1. A number of doors, windows, or wall louvers were open in a structure. In such cases, the natural ventilation rate generally dominated the analysis (this air is not filtered).
2. The ventilating system air filters were of relatively low efficiency for carbon fibers or the system did not incorporate air filters.

In other cases, the fibers of interest provided an AETF value which served as an upper bound to the computed range. For example, the lower bound for the AETF in hospital surgical suites was estimated to be

0.0 based upon the extremely high efficiency of air filters typically applied and the supposition that no fibers will enter with infiltrating air. The upper bound, however, was estimated to be 3.5×10^{-4} by assuming that a small amount of infiltration will take place and that a small fraction of this air will successfully convey carbon fibers.

F.3.6 Ceiling Height

Since carbon fibers will settle out onto exposed room surface areas, and since the distance through which they must travel to the floor affects the AETF, it was necessary to provide a range of ceiling heights for the occupancy types of concern. This was a straightforward task involving personal observations and telephone calls and does not require further comment.

F.3.7 Dust Spot Filter Efficiencies

Appendix E.1 describes our efforts to evaluate the efficiency of various grades of air filters for capturing carbon fibers. It notes that filters for building air supply systems are typically rated on an atmospheric dust spot basis, and attempts to relate reported dust spot efficiencies to efficiencies expected for carbon fibers. Obviously, before such relationships can be utilized in our analysis, it is necessary to have knowledge of what types of filters are commonly utilized in various types of occupancies.

ASHRAE guidebooks, filter manufacturer product bulletins, and various papers in the literature provide guidance on the minimum filter efficiency recommended for use in occupancies of concern. One is, therefore, tempted to assume that these recommendations are widely complied with. Unfortunately, our site visits graphically displayed that such recommendations are more often than not ignored.

The higher the dust spot efficiency of an air filter, the higher is its replacement cost, and generally, the fan motor power requirement for an equal volume rate of air passage. In direct consequence, we often found (with a number of exceptions) that:

1. Building tenants cut costs by using lower efficiency filters than minimally recommended. A contact in a filter servicing company noted that the efficiency of filters used is often a function of the ability of filter sales personnel. It is not uncommon for a new account to be gained with the promise of lower costs and comparable efficiency, when efficiencies are not truly the same.
2. A similar contact stated that building architects sometimes do not specify filter efficiencies when obtaining bids from manufacturers of HVAC equipment. A manufacturer can minimize the bid price by including the crudest of filters, and often does so. The tenant continues to use this type of filter unless serious problems develop.
3. Similarly, architects themselves may minimize building costs by specifying less efficient filters than are desirable.

We are not implying in the above that anyone is wronging anyone else. Rather, we are attempting to demonstrate that cost is an important concern when it comes to filter selection, and that many are willing to make a tradeoff between the known costs for better filters and the less quantifiable costs associated with an increased dirt and dust level in a building. Thus, most of our selections for dust spot efficiency ranges are derived from personal observations, and only partly from recommendations in the literature.

F.3.8 Carbon Fiber Filter Efficiency

Given the filter efficiency analysis presented in Appendix E, one would presume it is a fairly straightforward task to select an efficiency for carbon fibers based upon the dust spot efficiency of a filter. Unfortunately, this did not turn out to be the case.

The relationships between dust spot and carbon fiber efficiencies generally presume that all filters are properly installed, i.e., that there are no routes around filters for contaminated air bypass and that the filters themselves have not been punctured or forced out of line. If there

should be bypass of air around or through a filter bank, and the amount of air is significant, the overall efficiency of the bank will be considerably less than otherwise predicted.

During a number of site visits we had the opportunity to visually inspect filter banks. In some cases, we noticed that great care had been given to minimize or eliminate air leakage. In a significant fraction, however, we noted gaps between filter holders, thin filters placed into wide tracks, short filters in long tracks (with loose metal plates inserted at one end to reduce leakage), and a number of individual filters which were misaligned or otherwise out of place. In consequence, we attempted to pursue this matter further.

In a conversation with the president of an HVAC system design and servicing company, we were told that probably 15 to 20 percent of the air can bypass filters through gaps in metal to metal or metal to cardboard mating surfaces in some systems designed for low-efficiency filters. It was further commented that personnel sometimes intentionally allow contaminated air to bypass filters to prolong the life of the filter bank and reduce pressure drops. One could surmise that this was not uncommon where low-efficiency filters are utilized.

The research director of a filter manufacturing company had no quarrel with a statement that 10 to 15 percent of air can bypass some low efficiency filter installations. Indeed, he noted that holders for low-efficiency filters are sometimes sloppily designed, and will bypass some air even when properly used. His company's designers argue that some leakage around such filters is unimportant, since better filters would be installed in place of or in series with such filters if there was a special need to reduce dust levels.

Where medium to high efficiency filters are used, the situation appears to be much better, and the holders are designed to minimize or eliminate leakage. Our contact above estimated there would be much less than 1 percent leakage around a filter of proper size in a properly designed holder. Nevertheless, he also guessed that 1 out of 5 installations with medium to high efficiency filters probably has a significant air leak.

The consequence of these findings is that we utilized the dust spot versus carbon fiber filter efficiencies previously cited mostly to define upper bounds of filter efficiencies. This was especially true where one could see the need for careful maintenance of internal air quality in a particular type of occupied space. For lower bounds, we used our judgment to assess whether significant bypass of contaminated air around filters is a likely occurrence. If it was likely, we adjusted filter efficiencies to account for the leakage.

F.3.9 Overall Computed Results

For each combination of occupancy type and penetration scenario considered, we computed a range of AETF values. The range is intended to encompass the variety of AETF values which would be expected if a large number of similar occupancies were surveyed in detail, and if precise AETF values could be determined for each.

F.4 DETAILED RESULTS

F.4.1 Aircraft on Ramps and Runways

Mechanical Air Change Rates

According to NASA interviews with aircraft manufacturers, aircraft ventilation systems provide approximately 20 air changes per hour (ACPH) when activated. All indications are that air is not recirculated.

Natural Ventilation Rate

When considering wind flow into an aircraft cabin, one must take into account the fact that the air is essentially flowing into a closed box. Thus, some part of inlet openings must allow exit of excess air, while other parts allow entrance. Additionally, one must note that air entering a cabin door can flow to the right or to the left, that no air may enter when the cabin door is on the leeward side of the aircraft, and that a negligible amount of air will enter the cockpit area if the cockpit door is closed.

A sensitivity analysis of the effects of various parameter values in the equation presented above, and the effects of inserting resulting Q_N values into the AETF equation indicated that:

1. High cockpit AETF values result from wind speeds of even a few mph through an open cabin door near an open cockpit door; and
2. The operational status of the aircraft's HVAC system has little effect on the AETF value when the wind speed is a few mph or more, and cabin and cockpit doors are open.

In consequence, we arbitrarily selected a wind speed of 4 mph, and based upon reasonable ranges of values for other parameters, computed an overall Q_N range of 23.6 to 158.4 ACPH. This range provides conservative results for the AETF value in all but a few cases. Where it is not conservative, the effects of any errors are not significant.

Infiltration Rate

Compared to a residence or other typical building, the habitable compartments of a commercial airplane with a pressurized cabin must be considered very resistant to air infiltration. Wishing to be conservative, we therefore assign an infiltration rate range from zero (no infiltration) to 0.20 air changes per hour (ACPH), where the upper bound is approximately equivalent to the lower bound found for residences and other buildings (see appropriate section).

Crack Capture Efficiency

Crack capture efficiency is the fraction of carbon fibers prevented from flowing through a crack. We expect that any infiltration of air through the skin of the aircraft and around the well-sealed doors would involve openings sufficiently small to capture the majority of carbon fibers. However, we also realize the possibility that vents to the outside from equipment cabinets and toilets may allow relatively unimpeded inflow of contaminants when the ventilation system of the aircraft is not activated. Overall, we therefore estimate a crack capture efficiency range of 0.75 to 1.00.

Ceiling Height

Because of curved walls, we estimate the average ceiling height in a commercial airplane to lie in the range 5 to 7 feet.

Dust Spot Filter Efficiencies Recommended

Filters for aircraft are not to our knowledge rated on a dust spot efficiency basis. Recommendations in the literature, furthermore, do not specify filter efficiencies.

Carbon Fiber Filter Efficiency

NASA interviews with aircraft manufacturers have indicated that all planes have a water separating device incorporating an "Angora" type bag or sock. The efficiencies of such devices for removing carbon fibers from air streams will be determined in the near future by NASA-sponsored experiments. Pending the results of such experiments, we observe that lofted fabric bags are usually excellent particulate filters, and estimate that 50 to 99.5 percent of fibers will be captured by such a unit.

Boeing 727 and 737 aircraft, according to NASA interviews, also have some sort of metal filters with "veins." These are supposedly fairly effective for particles larger than 5 microns in size. Again, pending experimental results, we crudely estimate an efficiency range of 40 to 90 percent for carbon fibers. Since both types of filters would be in series, the overall filter efficiency range for these specific aircraft becomes 70 to 99.95 percent.

Overall Computed Results

When all aircraft doors are closed and the HVAC system is not activated, we estimate an AETF range of 0.0 to 9.2×10^{-4} . The specific type of aircraft is irrelevant in this case.

When one or more external doors are open, and the cockpit door is open, the range becomes 0.16 to 0.68 . It is not important if the HVAC system is on or off.

Because of differences in filtration practice between 727 and 737 aircraft and all others, a distinction must be made when aircraft doors are closed and HVAC systems are activated. For 727/737 craft, the estimated range is 1.0×10^{-4} to 8.2×10^{-2} . For all other craft, the range is 1.0×10^{-4} to 0.135 , with the larger upper bound reflecting uncertainties in the carbon fiber filtration efficiency of water separation devices.

F.4.2 Airport Baggage Make-up Areas

Mechanical Air Change Rates

These are garage type areas in which baggage is transferred between wheeled carts and motorized conveyor belts. Based upon a single observation, we presume that such areas are not economically heated or cooled by forced air ventilation systems. Thus, the mechanical ventilation rate is assigned a value of zero.

Natural Ventilation Rate

A computerized sensitivity analysis using the natural ventilation rate and AETF equations in combination allowed estimation of an overall range of AETF values when garage doors are open. Since the natural ventilation rate range was not explicitly defined, a range is not presented here.

Infiltration Rate

The garage doors through which the baggage carts enter and leave the terminal are quite large. Even in foul weather, they are opened often when the airport is operational. In consequence, we assume an infiltration rate range of 3 to 5 ACPH.

Crack Capture Efficiency

Since most infiltration would be attributable to the opening and closing of garage doors, we take no credit for a crack capture efficiency.

Ceiling Height

Based upon a single observation, we assume a ceiling height range of 10 to 12 feet.

Dust Spot Filter Efficiencies Recommended

Since we have presumed an absence of forced air ventilation in these areas, dust spot filter efficiencies are not pertinent.

Carbon Fiber Filter Efficiency

Not pertinent for reasons cited directly above.

Overall Computed Results

The AETF range estimated for the scenario with garage doors constantly open (i.e., pleasant weather conditions) is 0.32 to 0.87. When doors are only periodically opened, the range becomes 7.4×10^{-2} to 0.14.

F.4.3 Airport Control Towers

Mechanical Air Change Rates

ASHRAE Standard 62-73 addresses ventilation rates for control towers. Simple computations utilizing data provided indicate an overall range of 6.25 to 10.5 ACPH for total ventilation.

Minimum FAA ventilation requirements for radar and communications equipment rooms suggest rates of 5 to 6 ACPH or so, depending upon ceiling height. The range provided by ASHRAE appears appropriate for overall use therefore.

By analogy with recirculation practice in office buildings (see appropriate section below), we assume that 67 to 90 percent of air is recirculated in hot weather, zero to 10 percent in pleasant weather, and 50 to 90 percent in very cold weather.

Natural Ventilation Rate

A computerized sensitivity analysis using the natural ventilation rate and AETF equations in combination allowed estimation of an overall range of AETF values when windows are open. Since the natural ventilation rate range was not explicitly defined, a range is not presented here.

Infiltration Rate

An analogy of an airport control tower building with an office building provides an overall infiltration rate range of 0.2 to 1.0 ACPH.

Crack Capture Efficiency

We assume a crack capture efficiency range of 0.75 to 1.00 is fully conservative.

Ceiling Height

A visit to the control tower building at one airport indicated that a ceiling height range of 10 to 12 feet is an appropriate estimate.

Dust Spot Filter Efficiencies Recommended

FAA regulations specifically state that "The inclusion of highly sensitive electronic equipment in all ATCT facilities requires the use of high quality air filtration systems. Two-inch-thick, glass fiber filters, throw-away type, shall be used in all units. In addition to throw-away type filters, charcoal or high-efficiency type filters shall be installed in equipment serving critical areas. High-efficiency filters shall be rated at 95%

efficiency by AFI Standards. Electrostatic air filters should be considered when poor air quality conditions exist."

Discussions with personnel at a HVAC system servicing company, who have extensive knowledge of typical practice in airports, indicated that many newer airports utilize 85 percent efficiency (dust spot) final filters to reduce soot penetration. These are preceded by prefilters, and such configurations can be found at Dulles, Newark, Dallas-Fortworth, and maybe Kennedy. Thus, it is conservative to choose an upper limit value of 85 percent for final filters.

At Logan Airport in Boston we learned that all buildings, except the control tower, utilize 30 to 35 percent final filters. The control tower uses 50 percent efficient units. Thus, it appears that control tower buildings are given special consideration, and that an overall dust spot efficiency range is 50 to 85 percent for final filters.* Prefilter efficiencies for the two-inch disposable types cited above are typically on the order of 10 to 15 percent.

Carbon Fiber Filter Efficiency

Given a medium to high efficiency final filter preceded by one or more prefilters, we estimate a maximum credible fiber penetration of 0.1 percent. Our estimated filter efficiency range for CF is therefore 0.999 to 1.000.

Overall Computed Results

Sensitivity analyses with typical parameter values inserted into the natural ventilation rate and AETF equations indicated that relatively low wind speeds (4 mph, e.g.) and a couple of small open windows (5.0 sq ft total opening) could result in AETF values on the order of 0.5. With opening areas on the order of 1.0 sq ft, the AETF value dropped to roughly 1.3×10^{-2} . In consequence, we estimate a range of 1.3×10^{-2} to 0.5 when any windows are open in the control tower itself.

When windows are closed, we estimate an AETF range of 0.0 to 6.5×10^{-3} . The magnitude of the upper bound here is almost directly proportional to the product of the crack capture efficiency and the infiltration rate. If fiber penetration due to air infiltration was ignored, the range would become 0.0 to 2.5×10^{-4} with the upper limit due solely to fiber penetration through the filtration system.

* Late arriving data indicated the somewhat vague possibility that only 2-inch fiberglass filters are used at a regional airport. This matter requires further investigation.

F.4.4 Airport Passenger Terminals

Mechanical Air Change Rates

Repeated attempts to obtain actual mechanical air change rates for airline terminal buildings were unsuccessful. One specialist simply likened airport buildings to places of assembly and office areas, and suggested we refer to pertinent building codes. His main point was that there is nothing special about a passenger terminal, and that the range of recommended rates found in codes would be fully representative of current practice. In consequence, we utilized recommendations in ASHRAE Standard 62-73 to compute a range of 2.5 to 8.3 ACPH.

By analogy with office buildings, we assume 67 to 90 percent recirculation in hot weather, 0 to 10 percent in pleasant weather, and 50 to 90 percent in cold weather.

Natural Ventilation Rate

Our observations of various airports indicated it is rare to find constantly open doors or windows in passenger terminals. We were twice told that the soot and fumes from jet engines not only would cause soiling problems if doors and windows were opened, but would be physically distressing to passengers. (It appears that the fumes can cause headaches.) We, therefore, estimate a natural ventilation rate of zero.

Infiltration Rate

By analogy with office buildings we estimate a range of 0.2 to 1.0 ACPH.

Crack Capture Efficiency

We assume a crack capture efficiency range of 0.75 to 1.00 is fully conservative.

Ceiling Height

By observation of various terminals we estimate a ceiling height range of 9 to 18 feet. Although ceiling domes as high as 24 feet or so were observed, it was evident that air inlets were at lower levels.

Dust Spot Filter Efficiencies Recommended

Our contact at an HVAC system servicing company noted that many newer airports (including Dulles, Newark, Dallas-Fort Worth, and maybe Kennedy) commonly utilize 85-percent efficiency final filters preceded by prefilters. These are necessitated by the considerable quantities of very fine soot particles generated during startup and shutdown of jet engines. To reduce entrance of fumes, these filters are followed by carbon adsorption units in some areas of Dallas-Fort Worth, Detroit and Newark airports.

Boston's Logan Airport appears to be an exception. Here, one typically finds 35-percent final filters preceded by 10-percent efficient prefilters. All but one terminal uses carbon adsorption units to reduce fume concentrations, but since the particulate filters are not of high efficiency, the carbon beds are plugging rapidly in some areas. The terminal without the carbon bed is experiencing soiling problems.

Given these data, it is possible to conclude that terminal buildings at major airports require and generally have high efficiency filtration systems for particulate matter.

Carbon Fiber Filter Efficiency

Carbon adsorption units preceded by high and low efficiency air filters in series are likely to capture 100 percent of incoming carbon fibers. Nevertheless, to account for less sophisticated installations, we estimate an overall filter efficiency range of 0.999 to 1.000.

Overall Computed Results

Our estimated AETF range is 0.0 to 1.0×10^{-2} for airline passenger terminals with generally closed windows and doors and medium-to-high efficiency filtration systems. A single range is presented because seasonal recirculation practice had negligible effects upon the range predicted.

F.4.5 Airport Radar Transmitter Buildings

Mechanical Air Change Rates

A locked radar transmitter building observed from the outside at Logan Airport consisted of two attached mobile trailers with metal walls. Through one wall was placed an air-conditioning unit resembling home window units but on a larger scale. For such a configuration, we estimate a ventilation rate range of 4 to 10 ACPH.

Many air-conditioning units of this type only allow small amounts of fresh air entrance even when an adjustable damper is in the "fresh air" position. In consequence, we estimate that 85 to 100 percent of the air is recirculated within the structure.

Natural Ventilation Rate

It can be safely assumed that such structures are rarely found to have open windows or doors. The natural ventilation rate is, therefore, assigned a single value of zero.

Infiltration Rate

An infiltration rate range of 0.2 to 1.0 is considered representative for this type of structure.

Crack Capture Efficiency

A crack capture efficiency range of 0.75 to 1.00 is considered to be conservative.

Ceiling Height

The ceiling height observed was in the range of 8 to 9 feet.

Dust Spot Filter Efficiencies Recommended

We assume that the filter on this unit was similar to those commonly observed in other remote runway buildings. Since these were 2-inch spun glass throw-away types, their dust spot efficiencies would be on the order of 10 to 15 percent.

Carbon Fiber Filter Efficiency

It is likely that a 2-inch spun glass filter will capture more than 90 percent of carbon fibers if properly installed. Nevertheless, since there is some uncertainty as to the specific efficiency of such filters, we assign an efficiency range of 0.80 to 0.90.

Overall Computed Results

Our estimated AETF range for radar transmitter buildings is 0.0 to 1.1×10^{-2} .

F.4.6 Airport Runway Buildings (Miscellaneous)

Mechanical Air Change Rates

A number of small buildings near runways at Logan Airport housed various electronic equipments. Typically, these were converted mobile homes with metal walls, or well-constructed small shacks. Ventilation systems consisted of small window type air conditioners and/or exhaust fans drawing air through inlet ducts fitted with filters. For such configurations, we estimate ventilation rates ranging from 4 to 10 ACPH.

Where air conditioners were installed, one can safely estimate that 85 to 100 percent of the air is commonly recirculated. For the exhaust fan configuration, it is obvious that no air is recirculated.

Natural Ventilation Rate

A number of the buildings observed were manned on the day of our visit. Since the weather was pleasant, numerous doors and windows had been opened to increase ventilation.

A computerized sensitivity analysis using the natural ventilation rate and AETF equations in combination allowed estimation of an overall range of AETF values when windows or doors are open. Since the natural ventilation rate range was not explicitly defined, a range is not presented here.

Infiltration Rate

An infiltration rate range of 0.2 to 1.0 ACPH is considered representative for this type of structure.

Crack Capture Efficiency

A crack capture efficiency range of 0.75 to 1.00 is considered to be conservative.

Ceiling Height

Ceiling heights observed were in the range of 8 to 9 feet.

Dust Spot Filter Efficiencies Recommended

Systems utilizing exhaust fans were typically fitted with 2-inch spun glass filters of 10 to 15 percent dust spot efficiency. The window-type air conditioners utilized thin foamed plastic filters which probably have efficiencies on the order of 5 to 10 percent.

Carbon Fiber Filter Efficiency

An efficiency range of 0.8 to 0.9 is considered appropriate for these system configurations. It is likely that the 2-inch filters are somewhat more efficient than this range suggests, but there is little evidence to that effect. The thin foamed plastic filters may be somewhat less effective, but there should be some filtration efficiency associated with the wet cooling coils and other obstructions in the air conditioners. Overall, therefore, the selected range is considered appropriate.

Overall Computed Results

When windows or doors are open, the AETF can range from 1.9×10^{-2} to 0.61 depending on wind speed, window opening area, and a variety of other factors. The configuration of the mechanical ventilation system is not very important in such cases.

For closed buildings with window air conditioners operating, we estimate a range of 0.0 to 1.1×10^{-2} . For similar situations when the air conditioners are off, the range becomes 0.0 to 5.8×10^{-3} .

Buildings with operational exhaust fans and closed windows or doors are estimated to have AETF values in the range 7.7×10^{-3} to 4.2×10^{-2} . When the exhaust fans are off, the range is estimated to be 0.0 to 5.8×10^{-3} .

F.4.7 Computer Rooms

Mechanical Air Change Rate

ASHRAE guidelines indicate that less than 5 percent outdoor air will satisfy ventilation requirements in most computer rooms. Additionally, it is noted that outdoor air beyond the minimum is deleterious because the practice increases heating and cooling loads and makes control of atmospheric contaminants and winter humidity significantly more difficult.

Simple computations with data in ASHRAE Standard 62-73 suggest a ventilation rate range of 0.60 to 1.5 ACPH for computer room fresh air requirements, when ceiling heights range from 8 to 10 feet. This provides us a fresh air rate range for use in the analysis.

An assumption that about 95 percent of the total air supply will always consist of recirculated air then provides a recirculation rate of 11.4 to 28.50 ACPH, and a total estimated ventilation rate range of 12 to 30 ACPH.

Natural Ventilation Rate

Because of the common provision of specially conditioned environments for computer rooms, and the basic need to provide a filtered air supply, we observed that most, if not all, computer installations are not subjected to natural ventilation. A value of zero is, therefore, selected for this parameter.

Infiltration Rates

ASHRAE guidelines indicate that computer rooms should be maintained at net positive pressure relative to surrounding spaces to reduce or eliminate inward leakage of air. Our personal observation is that most computer installations of significant size are in internal building areas with special environments. In consequence, we estimate a typical infiltration rate range of 0.2 to 0.5 ACPH.

Crack Capture Efficiency

A crack capture efficiency range of 0.75 to 1.00 is considered conservative.

Ceiling Height

A range of 8 to 12 feet is considered typical for ceiling heights in computer rooms.

Dust Spot Filter Efficiencies Recommended

ASHRAE guidelines indicate a minimum dust spot efficiency of 20 percent for computer room air supplies, and a recommended efficiency of 45 percent when dry media filters are utilized. For electrostatic filters, the minimum is 85 percent, and 90 percent is recommended. Additionally, where the outdoor air contains unusually high quantities of dust, dirt, salt, or corrosive gases, higher efficiency filters or absorption chemicals are called for.

Discussions with personnel in an HVAC system servicing company indicated that they usually install or observe 30 to 35 percent efficiency dry media filters in computer room systems. It was noted that IBM minimally recommends 30 percent efficiency filters.

Carbon Fiber Filter Efficiency

Our best estimate is that a filter rated at 30 percent efficiency on a dust spot basis will capture on the order of 99.5 percent or more of carbon fibers. We, therefore, estimate an overall efficiency range of 0.99 to 1.00.

Overall Computed Results

The estimated AETF range for computer rooms is $0.0 \text{ to } 3.0 \times 10^{-3}$.

F.4.8 Elevators

Mechanical Air Change Rates

According to the National Elevator Institute, the American National Standard Code (ANSI A17) for elevators, dumbwaiters, escalators and moving walks is essentially enforced as law nationwide. This code requires that rooms containing machinery and control equipment be provided with natural or mechanical ventilation to avoid overheating of the electrical equipment. Additionally, with a few exceptions, it requires that elevators serving more than 3 floors be provided with means for venting smoke and hot gases to the outer air in case of fire. Usually, this latter requirement entails the provision of vents to the outer air during normal operation.

Those installations which utilize an exhaust fan in the machinery room often utilize a thermostat to activate the fan at high internal temperatures. Alternatively, mostly in warm climates, one may sometimes find that the machinery room is an air-conditioned space served by a central HVAC system. In all cases, however, according to the president of an elevator company, all machine rooms will have a vent to the outside.

Since the rate at which mechanical ventilation is to be provided is not specified in codes, and since it is therefore likely to vary widely, we assume the high overall mechanical ventilation rate range of 10 to 20 ACPH. Additionally, because of the conditions involved, we assume no recirculation of exhaust air.

Natural Ventilation Rates

We observed two configurations for the provision of natural ventilation to machine rooms. One involved a large grate between the machine room and a hoistway with an air vent. Otherwise, the machine room was essentially sealed. In the other case, the machine room not only had a grate to internal building areas, but additionally had a set of louvers built into its wall to the outside.

To assess the effect of natural ventilation, we performed a computerized sensitivity analysis using the natural ventilation rate and AETF equations in combination. The results of this effort are reflected in our overall computed results presented below.

Infiltration Rate

Although the effects of natural ventilation through vents to the outside will overshadow the effect of infiltration, we nevertheless assign a range of 0.2 to 1.5 ACPH.

Crack Capture Efficiency

Since machinery rooms are commonly maintenance-type areas on or near the tops of buildings, we estimate a crack capture efficiency range of 0.5 to 0.75.

Ceiling Height

A ceiling height range of 7 to 10 feet is consistent with our observations.

Dust Spot Filter Efficiencies Recommended

According to the president of an elevator company, air filters are "never used". Although we suspect that some air-conditioned rooms will have filtered air supplies, we nevertheless ignore the possibility of air filtration on the grounds that this practice is rare.

Carbon Fiber Filter Efficiencies

It follows from the above that this parameter has a value of zero.

Overall Computed Results

The AETF range we estimate for machinery spaces which are naturally ventilated and/or which have non-activated exhaust fans is 6.6×10^{-2} to 0.50, with the specific value for a particular room depending upon inlet opening area, wind velocity, and other factors. For rooms with activated fans, we compute a range of 0.16 to 0.35.

Door operator motors will always be found on top of elevator cars. By analogy with naturally ventilated machine rooms, we estimate an AETF range of 6.6×10^{-2} to 0.50.

F.4.9 Emergency Power Generators

General Observations

We observed numerous emergency power generators during visits to various facilities, and found that such units could be found in radically different environments. More specifically, by occupancy type, we found:

Airline Terminal Building: Generator was in air conditioned room on first floor.

Airline Reservations Bldg: Generator in metal enclosure with open ends placed outside.

Airport Main Emergency Units: In small masonry buildings (3) with exhaust fans and large louvered wall areas.

Hospital #1: In underground utility supply center; blower

	forces air in (no filters) when generator is operating or room becomes hot.
Hospital #2:	Two installations in basements and one on roof. All have air intake louvers without filters.*
Telephone Company:	Three units in air conditioned basement areas. A number of units on upper floors (of seven total) are essentially exposed to external atmospheres.
FAA Regional Center:	Unit(s) in metal building with exhaust fan and louvered inlets over high-performance air filters.

Obviously, a large fraction of these generator sets are exposed to the external environment to various degrees, while a smaller fraction are fully or partially protected. To properly account for the wide variation in potential vulnerabilities, we must define a set of scenarios which encompass our observations. In all cases, we are assuming that the generator sets are activated when a carbon fiber cloud passes.

Mechanical Air Change Rates

According to specification bulletins obtained from a manufacturer of motor-generator (MG) sets, two types of cooling systems are applied to MG sets. Radiator cooled units have large pusher fans which draw air volumes from the vicinity of the unit and discharge them through the radiator. These are usually larger models which provide from 12 to 750 kilowatts or so. Air-cooled systems are generally of lesser capacity, and utilize fans to force air through equipment housings. Since the radiator-cooled models require a greater airflow, and are more likely to be found at large installations, we confine our analysis to these types.

* Similar installations were seen in four buildings housing radio/TV studios or transmitters.

Using specifications provided, we estimate that the air-change rate through a factory provided housing is in the range of 5,000 to 6,000 ACPH. This is the range that units placed outside of a main building will experience in the worst case. If the MG set is installed in a small separate building, the larger volume of the building will tend to reduce the rates. We assume a ten-fold reduction to obtain 500 to 600 ACPH, with the realization that the results are not significantly sensitive at these orders of magnitude.

Units observed in internal building areas were placed in large rooms and did not have protective housings. When in air conditioned underground areas, they utilized filtered air supplies. Otherwise, they were found in areas with large louvered openings to the outside. We assume that rates of 10 to 60 ACPH adequately cover the situation when the units are operational.

Other Parameters

Estimation of natural ventilation rates, infiltration rates, and crack capture efficiencies is not warranted, since it is obvious that the large mechanical ventilation rates will dominate the analysis.

For ceiling heights, we select 6 feet for factory provided housings, and 12 feet for internal building areas. Again, our specific choice is non-critical.

Where the air is filtered, we assume a carbon fiber efficiency range of 0.76 to 0.99. This wide range encompasses the full variation expected within installations of utility supply equipment.

Overall Computed Results

When MG sets are in factory housings or small external buildings with non-filtered louvers, the AETF value is 1.0 for all practical purposes. If filters are provided, the range is on the order of 1.0×10^{-2} to 0.7, with the specific value depending on the fit and quality of the filters.

In large maintenance areas with non-filtered air supplies, the estimated AETF range is 0.24 to 0.66. In maintenance areas with air conditioning and filtered air supplies, the range becomes 2.4×10^{-3} to 0.16, and the specific value is again a function of filter fit and quality.

F.4.10 Health Facility General Areas

Mechanical Air Change Rates

Hospitals which acquire Federal funds under the Hill-Burton Program must comply with minimum standards of construction and equipment issued by the U. S. Public Health Service (USPHS). According to these standards, recovery rooms, intensive care areas, isolation rooms, examination rooms, treatment rooms, physical therapy and hydrotherapy areas, sterilizer equipment rooms, and food preparation centers have roughly similar minimum ventilation requirements. For all of these, we can choose a total ventilation rate range of 6 to 12 ACPH, and note that recirculation is not generally allowed unless high efficiency filters are utilized.

Natural Ventilation Rate

We assumed that any of the areas enumerated above, except possibly isolation rooms, may be subjected to natural ventilation through open doors or windows. In consequence, we utilized a computerized sensitivity analysis to define an AETF range when windows or doors are open to the outside.

Infiltration Rate

By analogy with office buildings, we assume an infiltration rate range of 0.2 to 1.0 ACPH.

Crack Capture Efficiency

A crack capture efficiency range of 0.75 to 1.00 is considered conservative.

Ceiling Height

Ceiling heights in two hospitals ranged from 8 to 12 feet.

Dust Spot Filter Efficiencies Recommended

Based upon observations in two hospitals, we expect common use of dust spot efficiencies ranging from 80 to 90 percent for final filters, and 10 to 35 percent for prefilters in building air supply systems.

Carbon Fiber Filter Efficiencies

We conclude that high efficiency filtration systems used in hospitals will capture 100 percent of carbon fibers.

Overall Computed Results

When windows or external doors are open, we estimate an AETF range of roughly 1.5×10^{-2} to 0.44, with the specific value depending upon wind speed, inlet opening area, and a variety of other factors. For the closed windows and doors scenario, we estimate a range of 0.0 to 6.5×10^{-3} .

F.4.11 Health Facility Laboratories

Mechanical Air Change Rate

The USPHS requires at least 2 fresh air changes per hour in general and media transfer laboratories. Minimum total air changes per hour are 6 and 4, respectively. Recirculation is not allowed in media transfer labs unless high efficiency filtration is provided. The practice is optional, however, in other labs.

Major labs in one hospital were ventilated at a rate of 10 ACPH, with all air being from the outdoors. We, therefore, select a range of 4 to 10 ACPH. Additionally, because of cross-contamination and other problems, we make the assumption that no air is recirculated.

Natural Ventilation Rate

As in previous cases, we used a computerized sensitivity analysis to provide an AETF range for open window conditions.

Infiltration Rate

Laboratories are often peripheral building areas with windows or doors to the outside. To ensure no outflow of contaminants to adjacent areas, many are maintained at negative pressure. In consequence, we select an infiltration rate range of 0.2 to 1.5 ACPH by analogy to residences.

Crack Capture Efficiency

A crack capture efficiency of 0.75 to 1.00 is considered conservative for hospital type buildings.

Ceiling Height

We found ceiling heights to range from 8 to 12 feet in two hospitals.

Dust Spot Filter Efficiencies Recommended

As best as can be determined, central HVAC systems in hospitals have high efficiency filtration systems and provide air to all parts of the hospital. Laboratories will often be served by such systems, even though they do not always require air of such extreme cleanliness.

Carbon Fiber Filter Efficiencies

Presuming we are correct in the above assessment, we can safely state that no carbon fibers will pass through the high efficiency filtration systems used in hospitals.

Overall Computed Results

For scenarios with closed windows and doors, we compute an AETF range of 0.0 to 1.0×10^{-2} . For labs with open windows, the range becomes 1.3×10^{-2} to 0.43 .

F.4.12 Health Facility Operating Rooms

Mechanical Air Change Rates

The USPHS requires a minimum total ventilation rate of 25 ACPH in operating rooms, with at least 5 ACPH consisting of outdoor air. Recirculation is not allowed except when the air is recirculated through two filter beds with 25 and 90 percent efficiencies, respectively, on the dust spot basis.

In two hospitals we found that 100 percent fresh air is used, with no desire to recirculate. One provided the 25 ACPH called for above, while the other provided 15 ACPH. A range of 15 to 25 ACPH is, therefore, considered appropriate for use.

Natural Ventilation Rate

Great care is taken to keep operating rooms free of external contamination. In consequence, one would not find open external windows or doors, and the natural ventilation rate can be assigned a single value of zero.

Infiltration Rate

Operating rooms are internal areas, usually maintained at positive pressure, and often specially designed to reduce or eliminate infiltration. We, therefore, choose an infiltration rate range of 0.0 to 0.2 ACPH.

Crack Capture Efficiency

For reasons similar to those enumerated above, we estimate a crack capture efficiency range of 0.90 to 1.00.

Ceiling Height

We found 10 to 12 feet ceiling heights in operating rooms of two hospitals.

Dust Spot Filter Efficiencies Recommended

The USPHS requires at least a 25 percent efficiency filter followed by a 90 percent efficient unit. Both hospitals surveyed exceeded these specifications. In one, air that had already been cleaned by a series 10, 20, and 90 percent filters was again passed through a high efficiency unit. In the other, 35 percent prefilters were followed by 95 percent or better final filters.

Carbon Fiber Filter Efficiency

Without reservation, we conclude that no carbon fibers can pass through properly designed filtration systems for operating rooms.

Overall Computed Results

Our estimated AETF range for operating rooms is 0.0 to 3.5×10^{-4} .

F.4.13 Health Facility Patient Rooms and Corridors

Mechanical Air Change Rates

The USPHS requires a minimum of 2 ACPH of fresh air and a minimum of 6 ACPH of total mechanical ventilation. One major Boston hospital told us the ventilation rate it provides is 6 ACPH. Between outdoor temperatures of 55 to 67F, about 100 percent fresh air is utilized. At other external temperatures, about 75 percent of the air is recirculated.

Another major hospital provides 8 to 12 ACPH in its new patient floors. About 85 percent of the air is recirculated, except in the summer, when somewhat less fresh air may be utilized.

Overall, it appears that the total ventilation rate in major hospitals can vary from 6 to 12 ACPH, while the percentage of recirculated air can vary from zero to 90 percent.

Natural Ventilation Rate

The USPHS requires that every patient room have a window which can be opened without the use of tools. In three of three hospitals, we found that many windows (all in one case) were open on pleasant days. As in previous cases, we used a computerized sensitivity analysis to provide an AETF range for open window conditions, and do not present a specific range of natural ventilation rates.

Infiltration Rate

The infiltration rate range of 0.2 to 1.0 ACPH found for office buildings is considered appropriate for application to health facilities.

Crack Capture Efficiency

A crack capture efficiency range of 0.75 to 1.00 is considered to be conservative.

Ceiling Height

Ceiling heights ranged from 8.5 to 9 feet in one hospital and 10 to 12 feet in another. The overall range selected for use, therefore, is 8 to 12 feet.

Dust Spot Filter Efficiencies Recommended

The USPHS requires at least 2 filter beds in patient care, treatment, diagnostic, and related areas. The first bed must be of at least 25 percent dust spot efficiency, while the second must be 80 or 90 percent efficient,

depending on whether or not all outdoor air is used.

The main HVAC system at one major hospital had a metal mesh filter on the outside of the building, followed by a series of 3 filter types. These respectively were 10, 20, and 90 percent efficient on the dust spot basis. At a second hospital, we learned of 85 percent final filters preceded by prefilters of at least 10 percent efficiency.

Carbon Fiber Filter Efficiencies

It appears that most major hospitals commonly utilize high efficiency filtration systems on inlet and recirculated air supplies. With the realization that there may be some exceptions, we conclude that such systems are 100 percent efficient for capture of carbon fibers.

Overall Computed Results

For patient areas with completely closed external windows and doors the estimated AETF range is 0.0 to 6.6×10^{-3} . When windows are opened, the range becomes 1.5×10^{-2} to 0.44 , depending upon a variety of factors.

F.4.14 Health Facility X-Ray Areas

Mechanical Air Change Rates

According to the USPHS, X-ray fluoroscopy and treatment rooms minimally require 2 ACPH of outdoor air and 6 ACPH of total ventilation. Fluoroscopy rooms should be at negative pressure and should not have HVAC systems which recirculate air from them.

At one hospital we did not learn of special treatment of X-ray areas. Rather, it appeared that the areas were simply provided 6 ACPH of ventilation. For a range, we therefore specify 6 to 10 ACPH. In regards to recirculation, we assign the entire range of 0.0 to 100 percent with full knowledge that our specific choice will not affect our computed results.

Natural Ventilation Rate

X-ray equipment rooms are often internal building areas. We would not expect to find open external windows or doors, and therefore estimate a single rate of zero ACPH.

Infiltration Rate

As usually internal building areas, we estimate X-ray rooms would have infiltration rates ranging from 0.2 to 0.5 ACPH.

Crack Capture Efficiency

A crack capture efficiency of 0.75 to 1.00 is considered conservative.

Ceiling Height

Ceiling heights in two hospitals ranged from 8 to 12 feet.

Dust Spot Filter Efficiencies Recommended

Based upon observations in two hospitals, we expect common use of dust spot efficiencies ranging from 80 to 95 percent for final filters, and 10 to 35 percent for prefilters.

Carbon Fiber Filter Efficiencies

We conclude that high efficiency filtration systems used in hospitals will capture 100 percent of carbon fibers.

Overall Computed Results

Our estimated AETF range for X-ray equipment areas is 0.0 to 3.3×10^{-3} .

F.4.15 Industrial Buildings

Mechanical Air Change Rates

We are attempting to deal here with a wide spectrum of building characteristics. At one extreme, we have the older type of facility without air-conditioning. Such a building may simply rely upon open windows, roof exhausters, wall fans, and/or local exhaust systems to provide ventilation with non-filtered air supplies. Sites we have visited include:

1. A machine shop (containing some computer controlled machinery) with wall fans and open windows in warm seasons, and sealed windows and the like in cold seasons.
2. A machine shop with open windows in warm weather, no wall fans, and recirculating exhaust air ventilation system at all times.
3. A chemical process building with numerous wall fans and an open garage door during most if not all seasons.
4. A series of chemical plant buildings (at one site) with open windows and doors and few mechanical sources of fresh air.

5. A chrome plating shop relying solely on air entering through a garage door for fresh air supplies in cold weather, and using wall fans in hot weather.
6. A dry cleaning plant which relies upon open windows, garage doors, and wall fans to moderate high internal temperatures during most seasons.

At the next level, we find somewhat newer or renovated buildings which may or may not have air-conditioning, but which do not rely upon open windows and the like for ventilation. Examples include:

1. A modern air-conditioned concrete block building without windows. It houses can filling and bottling lines as well as a semi-automatic batch chemical process area.
2. A building similar to the above, but which houses the production machinery for various types of springs.
3. A computer manufacturer with numerous production buildings. All have unopenable windows, double lock doors, and HVAC systems which maintain positive pressures throughout buildings.
4. A metal finishing company in a modern concrete block building without windows or air-conditioning, but with two large capacity make-up air systems supplying air to numerous local exhaust systems.
5. An old building devoted to automobile parts manufacturing. Make-up air units supply fresh air to local exhaust systems.

In the first category of buildings, we find some examples with no mechanical ventilation systems, and others with simple air moving systems. For these, we estimate a mechanical air change rate ranging from 0.0 to 20 ACPH.

In the second category, we have buildings with tempered air supplies. Air change rates for three buildings for which we obtained data were 0.72, 3.75, and 4.0 ACPH respectively. As an overall range, we believe 0.5 to 6.0 ACPH to be appropriate for general use.

Recirculation is not a common practice in buildings housing processes which generate dusts or gases. It is practiced in light production or assembly areas, however, and will typically involve zero to 90 percent of the total ventilation rate.

Natural Ventilation Rate

For the older, open-type buildings addressed above, specification of natural ventilation rates is not important. It is patently obvious that the upper bound of the AETF value range will be on the order of 0.6 from the results of other analyses. The lower bound will be that AETF predicted when windows and doors are nominally closed.

For the buildings with normally closed windows and doors, the appropriate rate is zero.

Infiltration Rate

We would expect the infiltration rates for the older types of buildings to be significant. Indeed, 0.5 to 3.0 ACPH is considered a reasonable range, with the understanding that the specific values chosen are not very important to final results.

In the second category of buildings, a range analagous to office buildings is more likely. We estimate 0.2 to 1.0 ACPH.

Crack Capture Efficiency

A range of 0.50 to 1.0 is estimated for the older type of building. The other category is assigned a range of 0.75 to 1.0 by analogy to office buildings.

Ceiling Height

Ceiling heights can obviously vary widely. Therefore, we select the wide range of 12 to 60 feet.

Dust Spot Filter Efficiencies

Most production processes housed in open-type factory buildings are unlikely to benefit from filtered air supplies. We will, therefore, assume that air filters are not utilized.

The HVAC systems serving the more modern types of buildings can be expected to utilize air filters in some instances. On a case-by-case basis, their presence will depend upon the nature of the operations conducted in the building, the extent to which management wishes to maintain a "clean shop," and the degree to which dust in external air soils internal surfaces. We, therefore, consider four scenarios; one without filters, one with low efficiency

filters only, one with medium-to-high efficiency filters, and one with high efficiency filters only. Additionally, we note that all four scenarios may be fulfilled in a single building when management is careful to choose the appropriate filter type for a specific type of production process.

Carbon Fiber Filter Efficiencies

For low-efficiency filters such as throwaway spun glass types, we compute a lower efficiency bound of 76.5 percent. This is done by assuming 10 to 15 percent air leakage around such filters, and a carbon fiber filter efficiency of 90 percent under laboratory conditions. The upper bound is chosen to be 95 percent by considering that one-inch spun glass filters are roughly 98 percent efficient for 12 mm carbon fibers under laboratory conditions, and that at least a few percentage points will be lost when they are used in the field.

For medium to high efficiency filters, we estimate the range of 99 to 100 percent efficiency for carbon fibers. The upper bound is supported by data presented in a subsequent appendix. The lower bound doubles the penetration expected through a 30 to 35 percent dust spot efficiency filter to account for air leakage.

When considering the sole use of high efficiency filters, we are addressing the clean room type of area to be found in some plants. Here, we assume that the filter banks will capture all carbon fibers.

Overall Computed Results

Our estimated AETF values are as follows for the scenarios considered.

A tight modern building with closed windows and no forced air system:

$$0.0 \text{ to } 6.4 \times 10^{-3}.$$

An older factory type building with closed windows and no forced air system:

$$3.9 \times 10^{-3} \text{ to } 0.2$$

As above, but with many open doors and windows:

$$0.3 \text{ to } 0.7$$

A tight modern building with mechanically provided, non-filtered air supplies:

$$1.5 \times 10^{-3} \text{ to } 0.48$$

As above, but using low efficiency air filters:

$$7.6 \times 10^{-5} \text{ to } 0.13$$

As above, but using medium to higher efficiency filters:

$$0.0 \text{ to } 3.3 \times 10^{-2}$$

As above, but using high efficiency filters for clean or semi-clean room conditions:

0.0 only.

F.4.16 Office Areas

Mechanical Air Change Rates

An ASHRAE guidebook notes that the total cfm of air per square foot for office buildings typically ranges from 0.75 to 2 (or more in special cases). Of this, about 0.25 to 0.4 cfm per square foot should be outdoor air (about 15 to 33 percent of the total flow is commonly recommended to be fresh air). Assuming 8 to 10 foot ceiling heights, we can compute a total ventilation rate range of 4.5 to 15 ACPH.

In field surveys of various buildings, and in a literature review, we found actual rates as low as 4 ACPH and as high as 12 ACPH. Thus, an overall range of 4 to 15 ACPH should cover the vast majority of cases.

Recirculation practice observed or otherwise learned about was fairly consistent. In hot summer weather, 3 of the 4 buildings for which we obtained data were recirculating about 90 percent of flow volumes. Thus, we conclude that an appropriate range is 67 to 90 percent, with the lower bound predicted by codes and ASHRAE recommendations.

In pleasant spring or fall weather, virtually all buildings apparently provide 90 to 100 percent fresh air because there is no energy penalty for the practice. In winter, 50 to 90 percent recirculation is common.

Natural Ventilation Rates

It is not uncommon to encounter office buildings with open windows, although the trend in the newest and tallest of buildings has been to provide sealed windows. To account for the effects of this practice, a computerized sensitivity analysis was conducted which utilized the natural ventilation and AETF equations in combination. The resulting AETF values are presented below.

Infiltration Rates

A literature search reported upon elsewhere in this report indicated that the infiltration rate for typical office buildings ranges from 0.2 to 1.0 ACPH.

Crack Capture Efficiency

The infiltration rate analysis cited above indicated that about 25 percent of inward air leakage is due to windows and doors. The remainder is due to leakage through walls, ceilings, and in the case of tall buildings, through elevator shafts. Assuming some fraction of carbon fibers will be captured by building materials as air infiltrates, we estimate a capture efficiency range of 0.75 to 1.00.

Ceiling Height

The ceiling height range for office areas is estimated to range from 8 to 10 feet.

Dust Spot Filter Efficiencies Recommended

Discussions with personnel at two HVAC systems servicing companies indicated that it is not uncommon to find modern office building HVAC systems with low efficiency (10-20 percent) filters. We observed their use at one building (2" fiberglass throwaway types) and learned of their use (polyester fiber blanket type) at one absolutely new skyscraper recently constructed, and at another modern skyscraper nearby. A pertinent

fact is that both tall buildings are located in a downtown area with high airborne concentrations of soot and dirt. Thus, their environment does not justify the use of such filters.

At one of these firms, we were told that there has been a trend in recent years towards the use of medium efficiency filters instead of high efficiency units. One example given involved yet another skyscraper built in recent years. This building utilizes 55 percent efficiency filters on upper floors, and uses prefilters for them only in systems which intake air near the street level. The prefilters are 2.5 or 3.0 inch spun glass filters of 15 percent or so dust spot efficiency. Another suburban building given as an example was said to utilize 35 percent efficient pleated bag filters.

At the other end of the scale, we learned of the use of 85 percent filters with prefilters at another tall building, and were told that the specification of such high efficiency units was common approximately 10 years ago. Overall, therefore, we find a broad spectrum of filter types being utilized in office buildings, and must separately estimate AETF values for buildings with low efficiency filters and those with medium to high efficiency units.

Carbon Fiber Filter Efficiencies

Our personal observations and discussions with various personnel indicated that low efficiency filters are prone to be sloppily installed when used in central HVAC systems. Although the filters themselves may be 90 percent or more effective for carbon fibers under laboratory conditions, leakage around frames and the like can cause significant efficiency reductions. By assuming 10 to 15 percent air bypass around filters, and by estimating an average efficiency of 90 percent for such filters

under ideal conditions, we therefore estimate a lower efficiency range bound of 76.5 percent. At the upper end, we choose an efficiency of 95 percent.

The situation for medium and high efficiency filters appears to be considerably better. We found more attention given to the design of filter frames, and a high likelihood that the filters would be properly installed. With the further determinations that filters rated at 35 percent should allow less than 0.5 percent penetration by carbon fibers, and that there should be considerably less than one percent air bypass around frames, we estimate a carbon fiber efficiency range of 0.99 to 1.00 for all installations with medium or high efficiency filters.

Overall Computed Results

Table F-1 presents the results of the analysis for all the various scenarios considered. Inspection of these indicates that it is possible to consolidate results for certain subsets of the scenarios because of similarities in AETF ranges predicted. The results of such an effort are listed below.

Any scenario with open windows:	1.2×10^{-2} to 0.63
Closed windows/med-hi eff. filters/any weather:	0.0 to 5.9×10^{-3}
Closed windows/low eff. filters/any weather:	4.3×10^{-4} to 7.0×10^{-2}
Closed windows/HVAC systems off:	0.0 to 6.4×10^{-3}
Closed windows/working unit ventilators:	0.0 to 1.5×10^{-2}

TABLE F-1

AETF VALUES FOR OFFICE BUILDINGS

<u>Windows</u>	<u>Weather</u>	<u>AETF for Low Eff. Filters*</u>	<u>AETF for Med/Hi Eff. Filters*</u>
Closed	Hot	4.3×10^{-4} to 2.8×10^{-2}	0.0 to 5.8×10^{-3}
Closed	Pleasant	3.8×10^{-3} to 7.0×10^{-2}	0.0 to 5.9×10^{-3}
Closed	Cold	4.3×10^{-4} to 3.9×10^{-2}	0.0 to 5.8×10^{-3}
Open	Hot	1.4×10^{-2} to 0.61	1.2×10^{-2} to 0.60
Open	Pleasant	1.9×10^{-2} to 0.61	1.2×10^{-2} to 0.60
Open	Cold	1.4×10^{-2} to 0.24	1.2×10^{-2} to 0.60

* For buildings with central HVAC systems which are operational.

Other Scenarios

Closed windows and HVAC systems off:	0.0 to 6.4×10^{-3}
Closed windows and operational unit ventilators:	0.0 to 1.5×10^{-2}
Open windows and operational unit ventilators:	1.2×10^{-2} to 0.61
Open windows and all HVAC systems off:	1.7×10^{-2} to 0.63

F.4.17 Radio Station Studio Buildings

Mechanical Air Change Rates

In a visit to the studios of two radio stations with combined operations, we estimated an air change rate of roughly 2 ACPH from review of building plans. With the judgment that this rate is unusually low, we select an overall range of 2 to 10 ACPH, with the upper limit being that observed in a television station studio building.

Insufficient data were available to assess the fraction of air recirculated in the installation surveyed. Nevertheless, it is apparent from our fieldwork that the fraction typically varies from 0.0 to 0.9 in various buildings.

Natural Ventilation Rate

Because of the necessity to minimize noise in studio areas, and for other reasons, we expect that open windows or doors would be rare in such installations. We, therefore, select the single rate of 0.0.

Infiltration Rate

The stations visited had taken extraordinary measures to minimize street noise and air leakage through window areas. Nevertheless, no unusual measures had been taken elsewhere in the rather old building, and we expect the infiltration rate range to be 0.2 to 1.0 ACPH.

Crack Capture Efficiency

The range of 0.75 to 1.00 is considered appropriate for an office-type building.

Ceiling Height

The dropped ceiling observed had a height of 8 feet. A range of 8 to 10 feet, therefore, appears to be appropriate for most installations.

Dust Spot Filter Efficiencies

The filters observed were one-half inch spun glass units which were installed in 2 to 3-inch wide tracks. This type of filter would not be rated on a dust spot basis because of its low efficiency. Indeed, it does not even qualify for furnace use in most residences. To provide more realistic coverage of typical installations, we therefore choose the range of 5 to 40 percent.

Carbon Fiber Filter Efficiencies

Taking into account the low efficiency of observed filters, and their rather sloppy installation, we estimate a lower efficiency bound of 0.70. At the other extreme, we note that some radio and TV stations give considerably more attention to filtration practice and choose a bound of 1.00.

Overall Computed Results

We estimate an overall range of 0.0 to 6.67×10^{-2} for radio station studio facilities.

F.4.18 Radio Station Transmitter Sites

Mechanical Air Change Rates

Visits to four transmitter installations situated within two buildings demonstrated an incredibly wide variation in ventilation practice. In consequence, we choose the ranges of 0 to 20 ACPH for the total ventilation rate, and 0.0 to 1.0 for the fraction of air recirculated.

Natural Ventilation Rate

None of the control room or transmitter installations were directly exposed to unfiltered air entering open windows or doors. Depending upon the status of various internal doors, however, some areas could be indirectly influenced. We account for such air supplies in the infiltration rate below, and consequently, set the natural ventilation rate here to zero.

Infiltration Rate

Extreme variation was observed, even within different areas of the same building. Overall, two control rooms and two transmitters were well protected from infiltration, while two of each were abnormally subject to its influence. Thus, we estimate an overall range of 0.2 to 3.0 ACPH.

Crack Capture Efficiency

Without presenting a myriad details, we again note extreme variation. Indeed, we estimate a lower bound as low as 0.5 and an upper bound of 1.0 without reservation.

Ceiling Height

Observed ceiling heights were all on the order of 14 feet. We, therefore, expect that the range of 12 to 16 feet adequately represents current practice.

Dust Spot Filter Efficiencies Recommended

The building air supply filters observed ranged from about 5 to 40 percent efficiency on the dust spot basis. Taking into account that some filters were placed in series, we estimate an overall range of 5 to 50 percent.

Carbon Fiber Filter Efficiencies

We estimate the range of 0.80 to 1.0 for filter efficiencies for carbon fibers. The lower bound is derived from consideration of a half-inch foam filter at one site. The upper bound considers the use of one 40 percent and two 10 to 15 percent dust spot efficiency filters in series at another site, and the indication that one station was striving for clean room conditions in a new transmitter building.

Overall Computed Results

The estimated range for control rooms and transmitters at radio station transmitter sites is 0.0 to 0.12. This is an abnormally wide range, but is necessitated by observed conditions.

F.4.19 Residences

Mechanical Air Change Rates

According to ASHRAE Standard 62-73, an appropriate ventilation rate range for residences with ceiling heights between 7 and 10 feet is 0.15 to 0.60 ACPH. With the understanding that all such air would usually be drawn from building spaces, and not from the outdoors, we utilize this range in computations.

Natural Ventilation Rate

The equation presented earlier for flow into openings is directly applicable to residences. To crudely estimate natural ventilation rates for residences, we consider a typical room and assume the following parameter ranges.

$A_w = 1.5 \text{ to } 3.5 \text{ sq ft}$

$V_w = 0.28 \text{ to } 8 \text{ mph} = 25 \text{ to } 704 \text{ fpm}$

$E = 0.25 \text{ to } 0.6$

Floor area = 125 to 375 sq ft

Ceiling height = 8 to 10 ft

These allow us to compute an overall range of 0.6 to 88.7 ACPH.

The inlet area range is estimated by simply assuming that one or two windows of roughly 30 inch width will be open to a height of 15 inches.

The lower bound of the air velocity range is the limit at which humans can perceive air movement. Even on a day with "still" air, one can expect velocities upto this value. The upper limit is derived from the modern Beaufort Scale. At or above this velocity, leaves and small twigs will be in constant motion, and light flags will be extended. By analogy, one would expect that window curtains may billow, venetian blinds may rattle, and that generally higher velocities would not be tolerated by inhabitants.

The range for effectiveness of openings is derived from the range provided by ASHRAE. There is an inherent assumption that the wind direction is at least marginally diagonal to open windows.

Other parameters are subjectively selected as limits for representative ranges with the realization that the final results are rather insensitive to the particular choices made.

Infiltration Rate

A literature search reported upon elsewhere in this report makes it clear that the infiltration rate for residences ranges from 0.2 to 1.5 ACPH.

Crack Capture Efficiency

The infiltration rate analysis discussed elsewhere indicates that 75 percent or more of infiltrating air enters through ceilings and walls of residences. Making the subjective judgement that all carbon fibers in such air will be captured by interior and exterior building materials (including insulation), and noting that some portion or all of fibers will not be successful penetrating cracks around windows and doors, we estimate that no more than 25 percent of fibers in infiltrating air will penetrate a residence. This provides a capture efficiency range of 0.75 to 1.0.

Ceiling Heights

The ceiling height range for residences is estimated to be 7 to 10 feet.

Dust Spot Filter Efficiencies Recommended

Furnace filters typically have dust spot efficiencies on the order of 8 to 12 percent. We assume that few residences utilize more efficient units.

Carbon Fiber Filter Efficiencies

According to the Research Director of a major air filter manufacturing, a good one-inch furnace filter should capture over 90 percent of carbon fibers. Since this was a subjective opinion, we choose an efficiency range of 0.80 to 0.90.

To properly consider the possibility that window screening might act as a carbon fiber filtration device, we contacted two screen manufacturers to determine the mesh dimensions of typical screens. Our findings that hole dimensions were on the order of 1.3 to 1.4 millimeters resulted in the decisions to take no credit for possible filtration by screens.

Overall Computed Results

For residences with open windows or doors, our estimated AETF range is 1.1×10^{-2} to 0.70, with the specific value being a function of inlet opening area, wind velocity, and other factors. It is rather irrelevant whether or not the residence has a forced air HVAC system or not.

When windows and doors are closed, and a forced air system is not operative or is non-existent, we estimate a range of 0.0 to 9.5×10^{-3} . With an operative forced air system, the range is 0.0 to 9.6×10^{-3} , so an overall range of 0.0 to 9.6×10^{-3} covers all residences well under these conditions.

F.4.20 Retail Outlets

Mechanical Air Change Rates

ASHRAE suggests 5 to 6 ACPH of total ventilation for normal load densities in department stores, 10 to 12 ACPH for heavy load densities, and 4 or less ACPH for economy, for areas with low occupancy and load density, or for areas with high ceilings. As an overall range, we therefore select 4 to 12 ACPH.

ASHRAE further suggests that at least one ACPH must consist of outdoor air. By analogy with practices observed in office buildings (see appropriate section), we estimate zero to 10 percent recirculation in pleasant weather, 50 to 90 percent in cold weather, and 67 to 90 percent in hot weather.

Natural Ventilation Rate

It is rare to find a large department store, supermarket, or other such outlet with open windows or doors. In consequence, we select a rate of zero ACPH for this parameter.

Infiltration Rate

Many stores with moderate to heavy traffic utilize air lock type entrances to reduce infiltration. Although infiltration rates may be somewhat higher on ground floors, we therefore expect that a range of 0.2 to 1.0 ACPH provides adequate coverage for buildings considered as a whole. In considering rows of cash registers near exits, however, we estimate the higher range of 1.0 to 2.0 ACPH. This is an exception to our assumption of perfect mixing.

Crack Capture Efficiency

A crack capture efficiency range of 0.75 to 1.0 is considered conservative when one is concerned with the average for an entire building. For areas near entrances and exits, however, we feel that an efficiency range of 0.25 to 0.75 is more appropriate.

Ceiling Height

Ceiling heights vary widely. We select the wide range of 10 to 18 feet to account for the majority of cases.

Dust Spot Filter Efficiencies Recommended

The filter supplier to downtown Boston's two largest department stores indicated that one utilizes a tackified pad type of filter of 25 percent dust spot efficiency, while the other uses 2-inch spun glass filters of 10 to 15 percent efficiency (or their equivalent).

Carbon Fiber Filter Efficiencies

We observed and were told that low efficiency filters are often sloppily installed. Assuming 10 to 15 percent air bypass for the 2-inch spun glass filters, and a 90 percent or so efficiency under ideal conditions, we estimate a lower efficiency bound of 0.765 for carbon fibers. At the other extreme, we note that tackified pad filters of 20 percent dust spot efficiency may capture well over 99 percent of fairly long fibers. Thus, we select an overall range of 0.765 to 0.99.

Overall Computed Results

The overall AETF range estimated for the internal areas of retail outlets is 9.4×10^{-5} to 9.0×10^{-2} . For cash register areas near busy entrances or exits, we estimate the range 5.2×10^{-3} to 0.12, with the specific value depending upon numerous factors.

F.4.21 Telephone Company Equipment Installations

Mechanical Air Change Rates

We visited the major telephone company building for the New England region and were told that the installation was typical in all respects. Mechanically provided air change rates were 4 ACPH in one older building section, and only said to be "somewhat higher" in a newer section. A range of 4 to 8 ACPH is therefore considered appropriate for general application.

Recirculation practice was not fully consistent with what we observed elsewhere. In pleasant and even hot weather, most areas receive 100 percent fresh air. In winter, 25 percent is recirculated down to freezing temperatures, then about 50 percent is recirculated. For short periods of time when the humidity is high, or the temperatures at night are extremely low, full recirculation may take place. We therefore characterize recirculation practice by noting that 0.0 to 50 percent recirculation is most common.

Natural Ventilation Rates

Strict company policy requires that all windows and doors be kept closed. In consequence, we select a rate of zero for all telephone equipment areas.

Infiltration Rate

To ensure that windows are not opened, and to reduce infiltration, all external windows were covered with yet another window which cannot be opened without a special tool. All edges were then taped to further eliminate inward leakage. To reduce infiltration further, the newer building section is pressurized. This is also attempted in the older building section, but is not quite as successful because of various leaks.

Overall, we note the special measures taken, but resort to an estimated range of 0.2 to 1.0 ACPH for analysis purposes. Although infiltration may be somewhat less than the stated upper limit in this particular building, we have no proof that this may be the case in all buildings of this type.

Crack Capture Efficiency

A crack capture efficiency range of 0.75 to 1.00 is considered conservative for this type of occupancy.

Ceiling Height

Observed ceiling heights ranged from 10 to 14 feet.

Dust Spot Filter Efficiencies Recommended

A number of different filtration systems were utilized at this large complex. The newer building section was served by an HVAC system fitted with prefilters and high efficiency filters in series. The prefilters were either lofted fabric cubes (specially oil-soaked with a dust spot efficiency over 30 percent), or were of the roll media type with dust spot efficiencies on the order of 10 to 15 percent. The high efficiency units were pleated bag types of high loft fabric. These were rated at 85 percent efficiency. In some cases, the air was further filtered with filter cubes, 2 inch spun glass filters, or 40 percent efficient extended media filters before it entered specialized areas such as computer rooms.

In the older building section, with few exceptions, only the fabric cubes were utilized. Exceptions involved two HVAC systems which utilized high efficiency final filters.

A random check of four filter banks revealed that there was little chance of unfiltered air passing through. The cube and pleated bag filters were properly installed and provided excellent edge seals. Problems observed with one roll filter and a bank of 2 inch spun glass filters were not significant, since neither type was used without a high efficiency backup.

Carbon Fiber Filter Efficiencies

We conclude that the 85 percent final filters preceded by prefilters will not allow entrance of carbon fibers into the newer building section. The situation for the older building section is somewhat unclear because of the liberal use of liquid adhesive on the cube filters. Although we suspect that these filters would successfully capture all fibers, we make the conservative assessment that they are 0.99 to 1.00 efficient.

Overall Computed Results

For the newer building section, we estimate an AETF range of 0.0 to 7.8×10^{-3} . For the older section, we estimate 0.0 to 9.2×10^{-3} .

F.4.22 Television Station Studio Buildings

Mechanical Air Change Rates

Although exact figures were unavailable, a knowledgeable source estimated that the air change rate for most areas of a television station we visited ranged from 6 to 10 ACPH. Exceptions involved the on-camera studios where the hot lights necessitated a rate on the order of 60 ACPH. The ranges of 6 to 10 ACPH and 40 to 60 ACPH are, therefore, considered appropriate for general application.

The station we visited currently recirculates about 90 percent of its air at all times. Since this wastes energy during certain times of the year, systems are being converted to automatically allow entrance of 100 percent outdoor air within certain temperature limits. In consequence, we note that the fraction of air recirculated may typically range from 0.0 to 0.9.

Natural Ventilation Rate

The station visited was essentially windowless. Because of potential security problems, all doors are kept locked. For this and other reasons involving noise, a rate of zero is considered appropriate for use.

Infiltration Rate

We expect that the building visited had a low infiltration rate. To provide coverage of all buildings of this type, however, we assume a range of 0.2 to 1.0 ACPH.

Crack Capture Efficiency

A range of 0.75 to 1.00 is chosen by analogy to office buildings and other structures.

Ceiling Height

Observed ceiling heights through most areas containing electronic equipment ranged from 10 to 12 feet. In on-camera studios, we observed a height of 18 feet and expect that a range of 16 to 20 feet is appropriate.

Dust Spot Filter Efficiencies Recommended

The station utilized 35 percent efficiency pleated filters in all HVAC systems. A source told us that the filter banks are not very tight and that station personnel are not very diligent in providing them proper maintenance. These comments explain our observation of significant dust accumulations on air diffusers and nearby ceiling areas.

With the assumptions that some stations utilize more efficient filtration systems, and that 35 percent efficiency is about the minimum necessary for an occupied building housing expensive electronic equipment, we choose an overall dust spot efficiency range of 35 to 50 percent.

Carbon Fiber Filter Efficiencies

Available information indicates that a properly constructed bank of 50 percent dust spot efficiency filters can capture virtually 100 percent of incoming carbon fibers. It also suggests that a poorly constructed or maintained set of 35-percent filters of the type observed might bypass 10 to 15 percent of contaminated air. Thus, we select an overall efficiency range of 0.85 to 1.00.

Overall Computed Results

We estimate the AETF range of 0.0 to 4.1×10^{-2} for general station areas. In on-camera studios, because of the high ventilation rate, the range becomes 0.0 to 0.10.

F.4.23 Television Station Transmitter Sites

Mechanical Air Change Rates

We are concerned here with the total ventilation rate through transmitter housings, and the rate through control rooms containing monitoring and control equipment. In the one installation we visited, it was noted that separate air-handling systems were installed, and we could understand the logic behind such a design configuration.

A control room is apt to be manned. To provide a comfortable environment in hot weather, the station we visited had installed two large packaged air-conditioning units in a relatively small room. Both of these had ducts to and from the outside. Thus, we estimate a ventilation rate range of 10

to 20 ACPH, and we presume that 50 to 90 percent of the air is recirculated when the units are activated. We also consider a scenario with a rate of zero, because the units observed were not activated on the cool autumn day of our visit, and there were space heaters in the room.

The transmitters generate considerable amounts of heat and must constantly be cooled with large amounts of air. The installation visited simply utilized a fan to force outdoor air through air filters, through the transmitter housings, and then directly outside. We could not determine the actual air change rate, but can safely estimate a range of 20 to 40 ACPH.

Natural Ventilation Rate

Although the building visited was windowless and well-sealed, a nearby building housing the transmitter for another station had a number of windows. Most of these were wide open to a central room containing the monitoring and control equipment. We suspect that this practice is rare for most installations, but must acknowledge the possibility of its occurrence. Thus, we performed a computerized sensitivity analysis to obtain a range of AETF values for open window conditions, making the assumption that the HVAC system was not activated while most of the windows were open.

Infiltration Rate

The installation visited was windowless and had a few metal doors with weatherstripping. Built of concrete blocks with a brick facing, it must be assumed to have quite a low infiltration rate under most conditions. Two other such buildings observed from outside were similar in construction but had windows. Thus, we make an analogy with office buildings in general and select an infiltration rate range of 0.2 to 1.0 ACPH for the control rooms. Because of high positive pressures, we ignore this effect in transmitter areas.

Crack Capture Efficiency

By further analogy to office buildings, we estimate a crack capture efficiency range of 0.75 to 1.00.

Ceiling Height

We expect that the range of 12 to 16 feet adequately represents current practice in control rooms. Six to eight feet is probably adequate for transmitter cooling areas.

Dust Spot Filter Efficiencies Recommended

The air-conditioners in the main room utilized 2-inch spun glass filters. The system for the transmitters utilized 35 percent efficiency pleated filters. Based on our observations at this site and at four radio transmitter installations, we conclude that efficiencies can range from 10 to 40 percent for systems serving the control room, and will be 20 to 40 percent or more for transmitter cooling systems.

Carbon Fiber Filter Efficiencies

Noting the propensity for spun glass filters to be poorly installed, we estimate a carbon fiber efficiency range of 0.765 to 1.00 for filters serving control rooms. Assuming somewhat better maintenance for transmitter filters, we estimate the range of 0.95 to 1.000 for these.

Overall Computed Results

For the control room, we have three scenarios. With open windows and the HVAC system off, we find an AETF range of 3.2×10^{-2} to 0.16. For closed windows and the HVAC system off, we estimate 0.0 to 1.0×10^{-2} . For closed windows and the HVAC system on, we get 0.0 to 6.2×10^{-2} .

For the transmitter housing system itself, the estimated range is 0.0 to 2.3×10^{-2} .

F.4.24 Utility Supply Areas

Mechanical Air Change Rates

Utility supply areas in large buildings are those areas housing HVAC systems, power conditioning or distribution equipment, telephone switching equipment, and any other equipment which supports the function of the building. In our surveys, we noted a significant variation in the types of environments which constitute such areas.

In at least some locations, power distribution and/or conditioning equipments were placed in closed rooms without ventilation, or in rooms with natural ventilation. The mechanical ventilation rate in such cases is obviously zero. In other locations, equipment could be found in areas simply ventilated with exhaust and/or supply fans. These fans were thermostatically controlled to activate under high heat conditions. Finally, one sometimes found such installations in air-conditioned areas with filtered air suppliers.

Where ventilation is mechanically provided, we assume ranges of 4 to 15 ACPH, and 0 to 50 percent recirculation. These ranges are consistent with that found for office areas in general, and recognize that some air-conditioned spaces housing equipment of concern were originally designed as multi-purpose areas, i.e., the entire building was designed to be served by the central HVAC system, and a tenant decided at a later date where to locate specific equipment.

Natural Ventilation Rate

A large maintenance type area in the basement of a large building, or on upper floors for that matter, is prone to have open doors, windows, or louvers, regardless of whether or not the space is air-conditioned. This statement, of course, is especially true in pleasant weather, and is supported by our observations in various buildings.

To assess the effect of natural ventilation, we performed a computerized sensitivity analysis using the natural ventilation rate and AETF equations in combination. The results of this effort are reflected in our overall computed results presented below.

Infiltration Rate

We expect that the infiltration rate into utility supply areas will be comparable to but somewhat greater than that into general office areas. We therefore select a range of 0.2 to 1.5 ACPH.

Crack Capture Efficiency

For similar reasons, we expect that the crack capture efficiency range will be somewhat lower than for general office spaces. We therefore select the range of 0.50 to 0.75.

Ceiling Height

A ceiling height range of 10 to 12 feet is consistent with our observations.

Dust Spot Filter Efficiencies Recommended

Where air filters are utilized for supplies to utility supply areas, we assume that they are in the low to medium efficiency range on the average. We never encountered a situation inconsistent with this statement in our field survey.

Carbon Fiber Filter Efficiency

Based upon previous decisions regarding carbon fiber filter efficiencies, we estimate the range of 0.765 to 0.99 for low to medium efficiency filters.

Overall Computed Results

For closed rooms without ventilation, we estimate an AETF range of 1.3×10^{-3} to 2.3×10^{-2} . With open windows, doors, or louvers to the outside, the range becomes 9.6×10^{-2} to 0.50.

For spaces ventilated with fans only, we assume no air filtration and compute the range 9.6×10^{-2} to 0.34. With air filters and central HVAC systems, the range estimated is 1.7×10^{-3} to 9.7×10^{-2} . If in either of these latter scenarios there are also open doors, windows, or louvers to the outside, the upper bound of the respective ranges becomes approximately 0.50.

G. INPUTS TO SIMULATION MODEL

G.1 INTRODUCTION

The simulation model described in Chapter 10 was used to develop a conditional risk profile for each large hub city. This required the compilation and entry of a large amount of data, describing the accidental release conditions, the weather conditions, and the characteristics of exposed facilities. Some of the data were entered as probabilistic distributions, while other data were deterministic in nature. The definitions and discussion of all the input variables may be found in Chapters 4, 5, and 9. Development of the transfer function and vulnerability estimates were described in Chapters 7 and 8, respectively.

This appendix presents tabulations of three types of data. The first section presents all data associated with the source of a carbon fiber release, namely a commercial air carrier accident. These data determine the initial conditions for a dispersion calculation. The second section presents all data associated with the impact of carbon fiber dispersion upon the exposed equipment. Finally, the third section presents data associated with the resulting economic losses to the community. Many of these tabulations give specific data for each of the 26 cities that were considered.

G.2 ACCIDENTAL RELEASE CONDITIONS

Given that an accident occurred, the amount of fuel burned and the carbon fibers released depended upon the accident type as well as the aircraft type. The assumed quantities were deterministic estimates, as shown in Tables G-1 and G-2. These variables were independent of the city at which the accident took place.

Weather conditions and aircraft type, however, were probabilistic variables, and varied from one city to another, due to differences in climate and fleet mix. The distributions of these variables, as well as the runway orientations for each city, are presented in Table G-3.

U.S. statistics on climate are not compiled in standard international units. For convenience, the inputs to the simulation model were left in

their original units. The following conversions apply to the temperature and wind distributions in Table G-3:

$$1 \text{ knot} = 1.85 \text{ km./hr.}$$

$$\text{Temp. (}^{\circ}\text{K)} = 5/9 [\text{Temp. (}^{\circ}\text{F)} - 32] + 273.15$$

G.3 FACILITY CHARACTERISTICS

After a carbon fiber release had occurred, and exposures at various locations had been computed, the interior exposure for each facility category was computed. Distributions were assumed for the types of buildings found in each facility category, and a range of transfer functions was estimated, as described in Chapter 7. These data are presented in Table G-4, and were assumed to apply uniformly to all cities.

To compute the economic losses resulting from a given accident, the simulation model used data on numbers of facilities exposed, amount of equipment per facility, and mean dosages for equipment failure. Table G-5 presents the facility and equipment characteristics used to determine expected number of failures and repair costs. Except for number of facilities, these data were assumed uniform across the U.S. The numbers of facilities were obtained for 25 facility categories in 40 sectors, for each of 26 cities. These are too voluminous to present here, but have been stored for future use. However, Table G-6 lists sources of the numbers of facilities and average revenue per facility for each facility category. The revenue data were also city-specific, and are discussed below.

G.4 ECONOMIC LOSS DATA

Having determined the expected number of failures, the simulation model then computed the economic losses based upon the repair costs shown in Table G-5, as well as upon average revenues in the case of critical or disruptive losses. The average revenues were obtained from 1972 census data, and then corrected to reflect 1977 dollars.

TABLE G-1FUEL BURNED UNDER VARIOUS SCENARIOS

<u>PHASE</u>	<u>LOCATION</u>	<u>DAMAGE</u>	FUEL BURNED (LITERS) BY AIRCRAFT TYPE		
			<u>SMALL</u>	<u>CONVENTIONAL</u>	<u>LARGE</u>
Take-off	On Airport	Substantial	1,000	1,667	6,667
Landing	On Airport	Substantial	300	500	1,667
Static	On Airport	Substantial	300	500	1,667
Take-off	Off Airport	Substantial	3,000	5,000	20,000
Landing	Off Airport	Substantial	1,500	2,500	5,333
Take-off	On Airport	Total	5,000	8,333	33,333
Landing	On Airport	Total	1,500	2,500	5,333
Static	On Airport	Total	1,500	2,500	5,333
Take-off	Off Airport	Total	15,000	2,500	100,000
Landing	Off Airport	Total	4,500	7,500	16,000

TABLE G-2

CARBON FIBER AMOUNTS
RELEASED UNDER VARIOUS SCENARIOS

RELEASE TYPE	LOCATION OF ACCIDENT	DAMAGE	CARBON FIBERS (Kg) RELEASED					
			Small Craft		Medium Craft		Large Craft	
			1985	1993	1985	1993	1985	1993
Fire	On Airport	Total	11	45	15	68	46	205
Fire	Off Airport	Total	21	90	31	136	92	410
Explosive	On Airport	Total	26	112	38	170	115	517
Explosive	Off Airport	Total	26	112	38	170	115	517
Fire	On Airport	Substantial	5	23	8	34	23	103
Fire	Off Airport	Substantial	11	45	15	68	46	205
Explosive	On Airport	Substantial	11	45	15	68	46	205
Explosive	Off Airport	Substantial	11	45	15	68	46	205

TABLE G-3

DISTRIBUTIONS OF RELEASE CONDITIONS FOR 26 AIRPORTS

ATLANTA

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	360	300	180	120	Small: 46.1
$\Pr(\angle_o) =$ (takeoff)	48.4	51.6	0	0	Conventional: 47.4
$\Pr(\angle_o) =$ (landing)	48.3	01.7	48.3	01.7	Large: 6.5

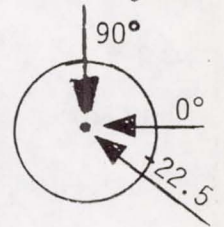
TEMPERATURE DISTRIBUTION

$\Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	-3.0	32.7	40.5	51.5	62.0	72.7	81.5	86.7	98.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$\Pr(\angle \leq \angle_o)$	0.0	15.6	18.0	30.1	50.4	65.4	77.4	89.8	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	41.7	100.0					00.8
B	15.8	65.8	100.0				06.5
C	04.6	29.9	91.5	100.0			11.2
D	02.8	18.0	59.8	95.0	99.5	100.0	46.1
E	16.0	69.4	100.0				35.4
F	--	--	--	--	--	--	0

BOSTON							Fleet Mix of Jets Utilizing Carbon Fibers in 1993 (Percent)
RUNWAY ANGLES, PERCENT UTILIZATION							
$\angle_o =$	20	70	140	200	250	320	Small: 35.2
$\text{Pr}(\angle_o) =$ (takeoff)	15	22	40	59	86	100	Conventional: 55.8
$\text{Pr}(\angle_o) =$ (landing)	8	27	50	58	77	100	Large: 9.0

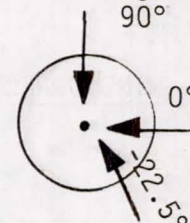
TEMPERATURE DISTRIBUTION

$\text{Pr}(T \geq T_o) =$	0.	.01	.05	.25	.50	.75	.95	.99	1.0
T_o	0	15	23	37	50	65	84	88	100

WIND DIRECTION

$\angle_o =$	0.	6.2	32.4	117.7	172.6	247.7	343.1	356.6	360
$\text{Pr}(\angle \leq \angle_o)$	0	1	5	25	50	75	95	99	100

for all angles:
90°



WIND SPEED AND STABILITY CLASS

CUMULATIVE (%)	STABILITY CLASS					
	A	B	C	D	E	F
0	5	1.5	1.5	1.5	3.5	1.5
1	5	1.6	2.2	2.6	3.6	1.5
5	5	2.2	4.0	4.6	4.3	1.7
25	5	4.4	6.9	8.7	6.5	3.3
50	5	6.2	8.7	12.0	8.0	4.6
75	5	7.7	10.4	14.4	9.3	5.6
95	5	9.6	15.0	19.4	10.2	6.3
99	5	9.9	18.0	24.4	10.4	6.4
100	5	10.5	22.0	30.0	10.5	6.5
CUMULATIVE PROBABILITY OF CLASS	A .03	B 2.34	C 10.9	D 80.0	E 94.0	F 100.0

CHICAGO

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	360	310	230	180	130	50
$Pr(\angle_o) =$ (takeoff)	08.0	13.7	02.0	37.1	30.5	08.7
$Pr(\angle_o) =$ (landing)	15.2	29.0	05.8	15.2	29.0	05.8

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

Small: 21.9
Conventional: 68.2
Large: 9.9

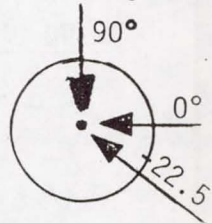
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	-20.0	14.1	28.1	33.8	47.1	62.4	74.3	82.7	97.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	6.8	17.0	27.0	40.5	59.8	76.9	93.1	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	63.0	100.0					00.9
B	20.8	69.5	100.0				05.3
C	09.6	35.6	90.9	99.4	100.0		10.7
D	03.3	23.0	63.2	94.4	98.4	100.0	52.7
E	28.1	81.5	100.0				30.4
F	--	--	--	--	--	--	0

CLEVELAND

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	360	270	220	180	90	40	Small: 33.5
$Pr(\angle_o) =$ (takeoff)	0	03.0	59.0	06.0	03.0	29.0	Conventional: 62.4
$Pr(\angle_o) =$ (landing)	03.0	03.0	44.0	03.0	03.0	44.0	Large: 4.1

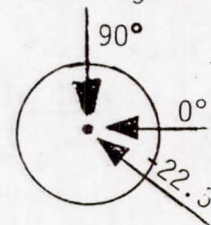
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	-14.0	18.6	28.6	35.0	48.3	62.4	73.8	81.1	98.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	4.2	13.0	25.9	35.2	48.9	71.9	94.3	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	51.2	100.0					00.3
B	20.4	59.5	100.0				03.5
C	05.3	24.5	87.1	98.6	99.4	100.0	09.7
D	01.3	15.0	47.7	89.5	98.3	100.0	29.7
E	03.0	15.9	58.7	92.5	98.7	100.0	34.4
F	18.8	75.7	100.0				22.4

DALLAS

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	90	100	140	270	280	320
$Pr(\angle_o) =$ (takeoff)	16.0	17.0	17.0	16.0	17.0	17.0
$Pr(\angle_o) =$ (landing)	16.0	17.0	17.0	16.0	17.0	17.0

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

Small: 15.9
Conventional: 79.8
Large: 4.3

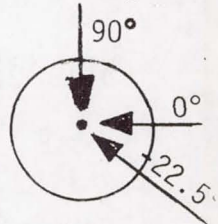
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	15.0	38.9	48.2	59.6	68.9	80.8	87.9	94.3	104.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	6.3	14.0	29.7	35.9	41.2	53.9	87.8	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	46.7	100.0					00.8
B	17.3	61.8	100.0				05.2
C	02.6	22.6	81.5	98.8	99.9	100.0	10.6
D	02.3	12.2	42.0	87.7	97.4	100.0	51.3
E	0	35.9	100.0				15.7
F	33.6	100.0					16.4

DENVER

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_0 =$	280	190	100	10	Fleet Mix of Jets Utilizing Carbon Fibers in 1993 (Percent)
$Pr(\angle_0) =$ (takeoff)	02.5	85.0	10.0	02.5	
$Pr(\angle_0) =$ (landing)	06.2	43.8	06.2	43.8	
					Small: 23.7
					Conventional: 78.8
					Large: 7.5

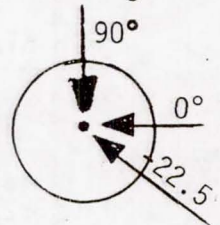
TEMPERATURE DISTRIBUTION

$Pr(T > T_0) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_0	-18.0	16.3	24.5	25.4	47.8	61.4	75.3	87.1	103.0

WIND DIRECTION

$\angle_0 =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_0)$	0.0	10.5	19.8	33.4	40.2	47.7	66.7	90.9	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	39.3	100.0					01.9
B	28.9	74.8	100.0				09.1
C	05.0	38.7	96.7	99.8	100.0		13.1
D	01.4	21.0	55.2	88.8	97.1	100.0	17.6
E	02.3	13.8	61.0	93.7	98.4	100.0	20.6
F	18.5	68.0	100.0				37.7

DETROIT

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	360	240	180	60	Small: 17.3
$Pr(\angle_o) =$ (takeoff)	25.0	25.0	25.0	25.0	Conventional: 74.3
$Pr(\angle_o) =$ (landing)	25.0	25.0	25.0	25.0	Large: 8.4

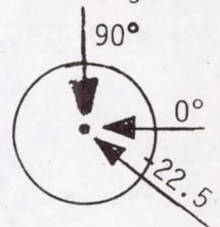
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	-14.0	15.9	26.7	33.2	45.7	60.7	74.3	82.3	99.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	10.6	18.0	28.8	40.0	60.9	76.3	91.1	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	50.0	100.0					00.2
B	17.8	54.7	100.0				02.9
C	03.5	23.5	88.4	99.3	100.0		09.8
D	01.5	10.4	47.9	92.8	98.7	100.0	66.1
E	15.0	61.4	100.0				21.0
F	--	--	--	--	--	--	0

HONOLULU

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	10	50	190	230	Small:	58.1
$\text{Pr}(\angle_o) =$ (takeoff)	25.0	25.0	25.0	25.0	Conventional:	19.4
$\text{Pr}(\angle_o) =$ (landing)	25.0	25.0	25.0	25.0	Large:	22.5

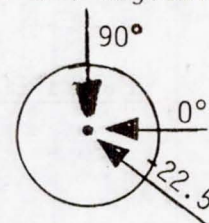
TEMPERATURE DISTRIBUTION

$\text{Pr}(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	54.0	63.5	65.0	67.0	68.6	81.8	83.6	84.5	94.0

for all angles:

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$\text{Pr}(\angle \leq \angle_o)$	0.0	46.7	75.3	83.1	85.8	87.8	90.6	96.6	100.0



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	46.5	100.0					00.1
B	26.0	63.1	100.0				02.6
C	03.4	14.9	58.8	89.9	99.0	100.0	12.1
D	01.2	07.4	37.6	87.7	98.4	100.0	55.8
E	0	43.5	100.0				16.3
F	34.5	100.0					13.1

HOUSTON

RUNWAY ANGLES, PERCENT UTILIZATION

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

$\angle_o =$	10	130	140	180	190	316	320	360	5.1 (Sm.)
$Pr(\angle_o) =$ (takeoff)	12.0	13.0	12.0	13.0	12.0	13.0	12.0	13.0	74.8 (Con.)
$Pr(\angle_o) =$ (landing)	12.0	13.0	12.0	13.0	12.0	13.0	12.0	13.0	20.1 (Lg.)

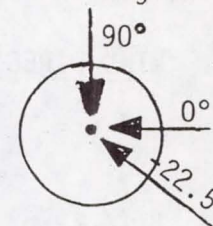
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	15.0	38.9	48.2	59.6	68.9	80.8	87.9	94.3	104.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	16.7	26.7	39.7	45.8	51.1	59.1	81.1	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	48.0	100.0					01.1
B	21.5	72.9	100.0				08.2
C	05.3	33.1	89.6	99.7	100.0		10.8
D	06.2	28.3	66.8	97.7	99.8	100.0	40.9
E	0	62.7	100.0				10.1
F	66.4	100.0					28.9

KANSAS CITY*

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	80	180	260	360	Small: 9.5
$Pr(\angle_o) =$ (takeoff)	25.0	25.0	25.0	25.0	Conventional: 89.6
$Pr(\angle_o) =$ (landing)	25.0	25.0	25.0	25.0	Large: 0.9

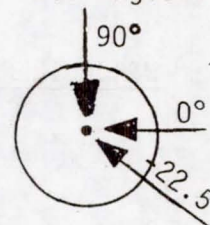
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	-13.0	21.0	32.3	41.2	55.0	68.8	77.4	88.0	107.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	7.2	15.3	27.6	40.2	47.7	63.2	88.7	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	48.5	100.0					00.7
B	22.0	68.7	100.0				04.7
C	05.8	25.1	86.4	99.3	100.0		11.2
D	02.1	13.0	50.7	95.1	99.5	100.0	55.4
E	19.2	66.0	100.0				28.0
F	--	--	--				0

KENNEDY

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	320	230	140	50	Fleet Mix of Jets Utilizing Carbon Fibers in 1993 (Percent) Small: 7.0 Conventional: 66.1 Large: 26.9	
$Pr(\angle_o) =$ (takeoff)	15.7	47.2	35.0	02.1		
$Pr(\angle_o) =$ (landing)	28.9	21.1	28.9	21.1		

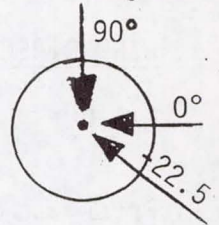
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	0.0	25.2	33.4	39.9	51.2	66.4	75.7	83.3	104.0

for all angles:

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	8.8	19.5	30.4	44.4	62.3	74.1	91.4	100.0



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	60.0	100.0					00.2
B	15.1	54.7	100.0				02.5
C	01.8	18.3	78.5	97.5	100.0		09.7
D	00.5	07.8	36.5	82.7	95.7	100.0	29.1
E	01.3	07.3	39.8	83.7	97.0	100.0	39.0
F	0	30.8	100.0				19.5

LA GUARDIA

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	320	230	140	50	Fleet Mix of Jets Utilizing Carbon Fibers in 1993 (Percent)	
Pr($\angle_o$) = (takeoff)	35.1	0	31.3	33.6	Small:	32.7
Pr($\angle_o$) = (landing)	17.9	32.1	17.9	32.1	Conventional:	63.8
					Large:	3.5

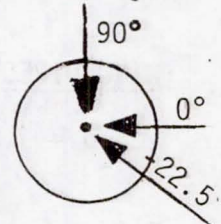
TEMPERATURE DISTRIBUTION

Pr($T \geq T_o$) =	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	1.0	26.0	34.0	40.7	52.1	68.0	75.6	83.8	107.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
Pr($\angle \leq \angle_o$)	0.0	8.8	22.4	36.5	55.5	71.2	84.3	96.8	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	14.2	100.0					00.2
B	13.2	59.4	100.0				03.6
C	01.5	24.8	84.0	99.6	100.0		09.4
D	00.6	12.0	45.9	91.0	99.0	100.0	28.2
E	02.1	12.2	53.1	92.7	99.0	100.0	36.0
F	0	33.4	100.0				22.6

LAS VEGAS

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$		
$Pr(\angle_o) =$ (takeoff)	Not Available when simulation was run. Distribution assumed was uniform. Orientations of runways are 20°, 80°, 200°, 260°.	Small: 49.8
$Pr(\angle_o) =$ (landing)		Conventional: 45.4
		Large: 4.8

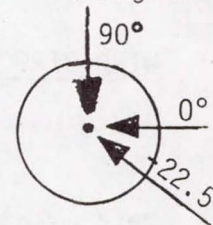
TEMPERATURE DISTRIBUTION

$Pr(T > T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	19.0	42.0	52.5	59.7	67.7	83.8	89.1	97.0	116.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	19.5	31.1	45.1	49.9	61.9	79.2	91.9	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	100.0						01.4
B	40.2	83.6	100.0				18.8
C	19.6	52.4	95.4	100.0			32.1
D	00.8	15.8	28.7	76.3	95.1	100.0	47.7
E	0	59.1	100.0				0
F	18.9	100.0					0

LOS ANGELES

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	210	200	30	20	Small: 14.4
$Pr(\angle_o) =$ (takeoff)	43.1	56.9	0	0	Conventional: 67.6
$Pr(\angle_o) =$ (landing)	22.8	27.2	22.8	27.2	Large: 18.0

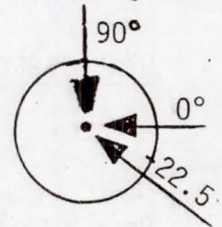
TEMPERATURE DISTRIBUTION

$Pr(T > T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	32.0	47.4	51.0	56.6	63.6	69.3	74.6	77.0	102.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	15.3	20.5	26.2	30.3	77.3	84.7	90.6	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	60.0	100.0					00.1
B	21.4	54.2	100.0				04.8
C	01.6	23.0	72.4	99.1	99.5	100.0	15.4
D	06.4	34.2	68.7	97.0	99.3	100.0	44.9
E	100.0						12.7
F	30.6	100.0					22.1

MIAMI

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	360	180
$Pr(\angle_o) =$ (takeoff)	33.0	67.0
$Pr(\angle_o) =$ (landing)	50.0	50.0

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

Small: 13.7
Conventional: 72.2
Large: 14.1

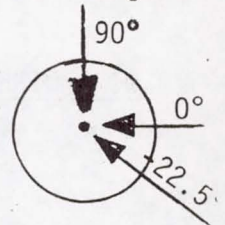
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	34.0	59.5	64.1	72.5	76.1	82.6	86.7	88.4	96.0

for all angles:

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	26.7	33.9	47.1	56.1	62.8	68.2	79.1	100.0



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	30.0	100.0					00.1
B	20.2	65.6	100.0				05.5
C	03.7	22.1	80.3	99.0	100.0		13.8
D	00.5	10.7	33.0	90.3	99.1	100.0	23.0
E	00.8	07.2	52.8	96.0	99.7	100.0	18.6
F	17.4	75.2	100.0				39.0

MINNEAPOLIS

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	340	230	160	50
$Pr(\angle_o) =$	41.7	26.8	17.7	13.8
(takeoff)				
$Pr(\angle_o) =$	32.3	17.7	32.3	17.7
(landing)				

Small: 26.3
Conventional: 65.1
Large: 8.6

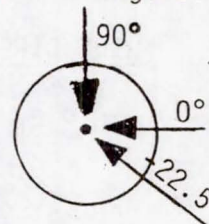
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	-34.0	0.9	18.8	25.6	39.8	59.5	69.8	82.8	101.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	7.3	14.0	30.5	46.2	57.0	67.7	86.0	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	44.0	100.0					00.3
B	24.8	66.9	100.0				03.6
C	12.2	31.6	85.9	99.0	99.9	100.0	09.5
D	01.5	14.9	44.4	91.9	99.0	100.0	31.8
E	03.0	13.4	53.1	94.6	99.2	100.0	28.7
F	0	38.7	100.0				26.1

NEWARK

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	340	230	160	50	Small: 29.8
$Pr(\angle_o)$ (takeoff)	07.1	50.3	10.5	32.1	Conventional: 63.6
$Pr(\angle_o)$ (landing)	12.2	37.8	12.2	37.8	Large: 6.6

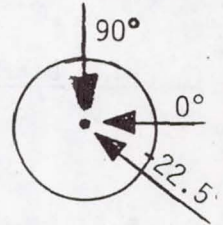
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	1.0	24.3	33.6	39.5	52.7	68.1	77.2	85.4	105.0

for all angles:

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	5.5	15.2	27.5	43.0	61.4	78.9	91.4	100.0



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	05.5	100.0					00.1
B	12.5	56.5	100.0				03.3
C	02.7	25.4	83.9	99.4	99.0	100.0	09.8
D	01.6	15.2	47.3	89.9	98.3	100.0	61.7
E	07.4	61.3	100.0				25.1
F	--	--	--	--	--	--	0

NEW ORLEANS

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	350	260	170	80	Small: 38.7
$Pr(\angle_o =$ (takeoff)	02.0	41.0	33.0	24.0	Conventional: 56.7
$Pr(\angle_o =$ (landing)	30.0	20.0	30.0	20.0	Large: 4.6

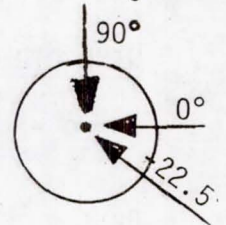
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	17.0	42.6	48.8	59.0	68.9	78.8	86.2	90.4	98.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	15.7	28.9	44.6	50.4	59.2	67.8	85.7	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	16.0	100.0					00.9
B	16.4	65.2	100.0				07.1
C	04.3	29.8	87.1	99.8	100.0		12.9
D	01.3	22.6	54.3	95.0	99.5	100.0	19.1
E	03.8	20.1	68.3	97.6	99.7	100.0	21.4
F	42.6	86.7	100.0				38.6

PHILADELPHIA

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	360	280	180	100
$Pr(\angle_o) =$ (takeoff)	36.0	0	64.0	0
$Pr(\angle_o) =$ (landing)	50.0	0	50.0	0

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

Small: 36.7
Conventional: 57.3
Large: 6.0

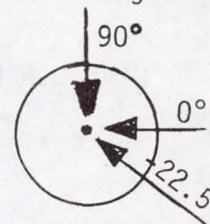
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	1.0	23.9	32.8	40.2	51.8	66.8	78.4	86.0	104.0

for all angles:

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	11.4	16.5	31.7	48.6	68.2	84.7	94.7	100.0



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	04.0	100.0					00.3
B	19.8	62.0	100.0				04.3
C	05.2	30.6	86.9	99.2	99.9	100.0	10.7
D	02.0	16.0	52.6	91.5	98.6	100.0	56.4
E	0	44.6	100.0				15.0
F	31.2	100.0					13.3

PHOENIX*

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	360	270	220	180	90	40	Small: 29.5
Pr($\angle_o$) = (takeoff)	0	03.0	59.0	06.0	03.0	29.0	Conventional: 65.9
Pr($\angle_o$) = (landing)	03.0	03.0	44.0	03.0	03.0	44.0	Large: 4.6

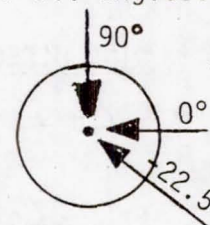
TEMPERATURE DISTRIBUTION

Pr($T \geq T_o$) =	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	19.0	42.0	52.5	59.7	67.7	83.8	89.1	97.0	116.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
Pr($\angle \leq \angle_o$)	0.0	20.7	24.4	30.1	39.6	60.9	66.5	73.8	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	31.1	100.0					02.4
B	28.9	39.0	100.0				11.6
C	04.7	37.9	91.7	99.7	100.0		17.3
D	00.8	20.0	54.0	93.2	98.5	100.0	11.4
E	02.6	09.5	61.5	95.7	99.4	100.0	09.5
F	23.5	78.2	100.0				47.8

PITTSBURGH

RUNWAY ANGLES, PERCENT UTILIZATION

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

$\angle_o =$	350	310	220	170	130	40	Small: 34.8
$Pr(\angle_o) =$ (takeoff)	17.0	17.0	16.0	17.0	17.0	16.0	Conventional: 63.8
$Pr(\angle_o) =$ (landing)	17.0	17.0	16.0	17.0	17.0	16.0	Large: 1.4

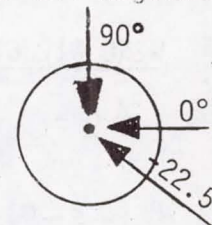
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	-10.0	19.2	29.3	36.1	48.0	48.6	74.7	82.7	98.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	9.0	15.1	26.5	42.4	65.8	78.6	89.4	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	21.4	100.0					00.2
B	23.7	67.6	100.0				03.6
C	07.9	33.4	90.5	99.5	99.9	100.0	08.8
D	01.3	17.1	50.1	91.4	98.5	100.0	29.3
E	03.6	21.0	65.1	94.8	99.0	100.0	31.0
F	0	56.0	100.0				27.1

SAN FRANCISCO

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	350	260	170	80	Small:	19.3
$Pr(\angle_o) =$ (takeoff)	04.7	01.6	34.4	59.3	Conventional:	67.8
$Pr(\angle_o) =$ (landing)	46.3	03.7	46.3	03.7	Large:	12.9

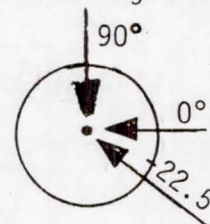
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	24.0	41.3	45.5	51.1	54.7	66.1	70.6	73.4	103.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	5.8	11.2	15.5	49.7	76.3	82.7	92.6	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	58.3	100.0					00.1
B	27.1	81.6	100.0				05.3
C	07.2	32.2	65.7	87.3	98.4	100.0	11.7
D	03.7	15.7	44.1	82.9	96.7	100.0	55.7
E	0	28.8	100.0				22.7
F	21.1	100.0					04.5

SEATTLE

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	290	110
$Pr(\angle_o)$ (takeoff)	60.0	40.0
$Pr(\angle_o)$ (landing)	50.0	50.0

Small: 11.2
Conventional: 80.0
Large: 8.8

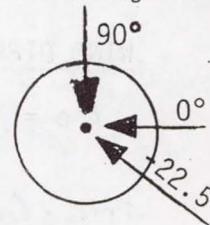
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	6.0	34.8	38.5	43.7	51.3	56.0	68.8	75.6	98.0

for all angles:

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	7.8	20.7	34.4	38.3	47.9	69.5	87.6	100.0



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	42.2	100.0					00.4
B	33.4	74.1	100.0				05.4
C	15.3	45.0	95.7	100.0			09.5
D	08.0	33.4	71.9	95.6	99.4	100.0	60.5
E	0	52.4	100.0				10.5
F	51.8	100.0					13.6

ST. LOUIS

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	330	210	150	30
$Pr(\angle_o) =$ (takeoff)	57.5	01.9	40.2	00.4
$Pr(\angle_o) =$ (landing)	47.2	12.8	47.2	12.8

Small: 44.1
Conventional: 54.4
Large: 1.5

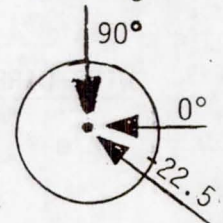
TEMPERATURE DISTRIBUTION

$Pr(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	-10.0	20.0	33.1	43.0	53.6	67.8	78.8	88.5	106.0

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$Pr(\angle \leq \angle_o)$	0.0	9.5	15.5	24.3	39.3	55.7	64.3	84.6	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	50.0	100.0					00.6
B	16.3	64.8	100.0				04.8
C	06.2	27.3	89.0	99.5	99.8	100.0	10.5
D	01.1	18.9	52.9	92.6	98.6	100.0	27.9
E	02.6	15.1	58.6	94.3	98.9	100.0	28.0
F	19.5	68.6	100.0				28.2

TAMPA

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_o =$	360	270	180	90	Small: 18.9
$\text{Pr}(\angle_o)$ (takeoff)	25.0	25.0	25.0	25.0	Conventional: 74.1
$\text{Pr}(\angle_o)$ (landing)	25.0	25.0	25.0	25.0	Large: 7.0

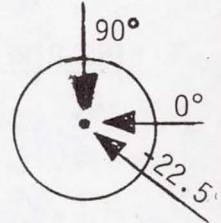
TEMPERATURE DISTRIBUTION

$\text{Pr}(T \geq T_o) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_o	31.0	55.0	62.0	72.0	78.0	83.0	87.0	89.0	103.0

for all angles:

WIND DIRECTION

$\angle_o =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$\text{Pr}(\angle \leq \angle_o)$	0.0	26.2	37.7	47.4	56.6	69.1	75.5	86.0	100.0



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	28.6	100.0					00.2
B	11.6	55.8	100.0				06.1
C	02.3	19.6	85.5	99.6	100.0		15.1
D	01.5	13.8	58.1	97.5	99.7	100.0	38.2
E	0	55.3	100.0				18.3
F	17.7	100.0					22.1

WASHINGTON, D.C.

Fleet Mix of
Jets Utilizing
Carbon Fibers
in 1993
(Percent)

RUNWAY ANGLES, PERCENT UTILIZATION

$\angle_0 =$	300	270	120	90
$\text{Pr}(\angle_0) =$ (takeoff)	11.0	33.0	06.0	50.0
$\text{Pr}(\angle_0) =$ (landing)	09.5	40.5	09.5	40.5

Small: 25.6
Conventional: 74.4
Large: 0.0

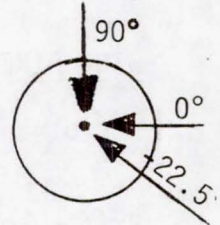
TEMPERATURE DISTRIBUTION

$\text{Pr}(T \geq T_0) =$	0.	.04	.16	.28	.48	.72	.84	.96	1.0
T_0	3.0	27.3	36.1	44.9	55.4	69.6	80.8	88.0	101.0

WIND DIRECTION

$\angle_0 =$	-22.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
$\text{Pr}(\angle \leq \angle_0)$	0.0	8.6	19.0	36.8	49.4	56.6	73.9	95.6	100.0

for all angles:



WIND SPEED AND STABILITY CLASS

WIND SPEED (KNOTS)

	0 - 3	4 - 6	7 - 10	11 - 16	17 - 21	>21	Pr (class)
Class A	25.2	100.0					00.6
B	23.4	73.9	100.0				06.7
C	06.7	39.2	93.0	99.7	100.0		11.3
D	03.2	25.4	56.6	92.7	98.7	100.0	23.3
E	05.1	22.2	63.7	94.5	99.1	100.0	27.0
F	17.8	74.5	100.0				31.1

TABLE G-4

DISTRIBUTION OF TRANSFER FUNCTIONS

<u>Facility and Building Category</u>	<u>Proportion of Bldgs.</u>	<u>Transfer Function</u>	<u>Range for Sensitivity</u>
1-Households			
Residences-Open Window	0.2	0.63	2.9×10^{-2} to 0.63
Residences-Closed Window	0.8	9.5×10^{-3}	0.0 to 9.5×10^{-3}
2-Police Cars	1.0	0.01	
3-Shipyards			
Open Window Building	0.5	0.61	1.4×10^{-2} to 0.6
Closed Window Building	0.5	3.9×10^{-2}	4.3×10^{-4} to 3.9×10^{-2}
4-Automobiles	1.0	0.01	
5-Post Office			
Office Type Building	1.0	3.9×10^{-2}	4.3×10^{-4} to 3.9×10^{-2}
6-Subway	1.0	0.6	10^{-2} to 0.6
7-Manuf. of Power Equip.			
Utility Supply Area	0.1	0.5	9.6×10^{-2} to 0.5
Ind. Bldg.	0.6	0.48	1.5×10^{-3} to 0.48
Ind. Bldg.	0.3	6.4×10^{-3}	0.0 to 6.4×10^{-3}
8-Manuf. of Elect.Computing Equip.			
Ind. Bldg.-Computer	0.5	1.4×10^{-2}	0.0 to 1.4×10^{-2}
Office Env.	0.4	5.9×10^{-3}	0.0 to 5.9×10^{-3}
Office Env.	0.1	0.63	1.2×10^{-2} to 0.63
9-Telephone Company Headquarters	1.0	7.4×10^{-3}	0.0 to 7.4×10^{-3}
10-Telephone Companies			
Tel. Company	1.0	7.4×10^{-3}	0.0 to 7.4×10^{-3}
11-Radio/TV			
Average Building for Radio/TV	1.0	5.0×10^{-2}	0.0 to 5.0×10^{-2}
12-Gas & Electric			
	0.5	1.0×10^{-2}	
	0.5	5.0×10^{-1}	

TABLE G-4 (Cont'd.)

<u>Facility and Building Category</u>	<u>Proportion of Bldgs.</u>	<u>Transfer Function</u>	<u>Range for Sensitivity</u>
13-General Merchandise Retailers			
Dept. Store-Away from door	0.8	9.0×10^{-2}	9.4×10^{-5} to 9.0×10^{-2}
Dept. Store-Near door	0.2	.12	5.2×10^{-3} to 0.12
14-Retail Grocers			
Dept. Store-Away from door	0.2	9.0×10^{-2}	9.4×10^{-5} to 9.0×10^{-2}
Dept. Store-Near door	0.8	.12	5.2×10^{-3} to 0.12
15-Financial and Insurance			
Office Bldg-Med/High Eff.	0.8	5.9×10^{-3}	0.0 to 5.9×10^{-3}
Office Bldg-Low efficiency	0.2	7.0×10^{-2}	4.3×10^{-4} to 7.0×10^{-2}
16-Business Services			
Office Bldg-Low Efficiency-Closed	0.8	7.0×10^{-2}	4.3×10^{-4} to 7.0×10^{-2}
Office Bldg-Low Efficiency-Open	0.2	0.63	1.2×10^{-2} to 0.63
17-Computer Services			
Office Bldg-Low Efficiency-Closed	0.8	7.0×10^{-2}	4.3×10^{-4} to 7.0×10^{-1}
Office Bldg-Low Efficiency-Open	0.2	0.63	1.2×10^{-2} to 0.63
18-Electronic R&D, Universities			
Office Bldg-Med Efficiency-Closed	0.8	5.9×10^{-3}	0.0 to 5.9×10^{-3}
Office Bldg-Low Efficiency-Open	0.2	0.63	1.2×10^{-2} to 0.63
19-Hospitals			
Operating Room, etc.	0.4	3.5×10^{-4}	0.0 to 3.5×10^{-4}
Patient Room-Open Window	0.4	0.44	1.5×10^{-2} to 0.435
Power Generator	0.2	0.16	2.4×10^{-3} to 0.16
20-Airplanes			
Closed Doors-HVAC off	0.5	9.2×10^{-4}	0.0 to 9.2×10^{-4}
Doors Open	0.5	0.68	0.16 to 0.68
21-Control Tower at Airport	1.0	6.5×10^{-3}	0.0 to 6.5×10^{-3}
22-Terminal at Airport	1.0	10^{-2}	0.0 to 10^{-2}

TABLE G-4 (Cont'd.)

<u>Facility and Building Category</u>	<u>Proportion of Bldgs.</u>	<u>Transfer Function</u>	<u>Range for Sensitivity</u>
23-ASR Field Radar			
Radar Transmitter Bldg.	1.0	1.0×10^{-2}	0.0 to 1.1×10^{-2}
24-LOC at Airport	1.0	0.6	2.10^{-2} to 0.6
25-VOR at Airport			
Open Window	1.0	0.6	2×10^{-2} to 0.6

TABLE G-5

FACILITY AND EQUIPMENT CHARACTERISTICS

<u>Facility and Equipment Type</u>	<u>Repair Cost per Unit</u>	<u>Level of Failure</u>	<u>Number of Equipment</u>	<u>Mean Dosage for Failure</u>
1-Households				
TV/Stereo	60	Repair	1	6.4E08
White Goods ***	60	Repair	3	5.0E06
Furnace	80	Repair	1	1.0E06
2-Police Cars				
Radio	200	Repair	1	1.0E06
3-Shipyards				
Minicomputers	1,200	Repair	4	4.9E06
Cranes	10,000	Repair	3	4.0E05
Terminals	150	Repair	4	1.0E07
4-Automobiles				
Radio	50	Repair	1	1.0E06
5-Post Office				
Sorter without Optical Character Reader	20,000	Repair	11	5.0E05
Sorter with Optical Character Reader	10,000	Repair	1	4.9E09*
6-Subway, Railroad				
Radio	150	Repair	190****	1.0E06
Motors	10,000	Repair	40****	1.0E07
Schedule System	150,000	Repair	1****	4.9E06
Auto Fare Coll.	18,000	Repair	3****	2.1E06
7-Manuf.-Power Equip.				
Tel. PBX	3,000	Disruptive	1	7.0E05
8-Manuf. of Electronic Computing Equip.				
Work-in-Process Inventory**		Critical	1	4.9E06
Tel. PBX	3,000	Disruptive	1	7.0E05

* Incorporates Computer Room Transfer Rate.

** Costs generated by using 2.5 x daily revenue for critical loss - 10% of 25 days inventory.

*** Kitchen appliances, e.g., stove, washer/dryer.

**** Number of pieces for entire Transit System; Varied by Metropolitan Area.

TABLE G-5 (Cont'd.)

<u>Facility and Equipment Type</u>	<u>Repair Cost per Unit</u>	<u>Level of Failure</u>	<u>Number of Equipment</u>	<u>Mean Dosage for Failure</u>
9-Telephone Companies				
Main Switching Center	2,000,000	Repair	2	7.0E05
Dedicated Tel. Sys.	500,000	Repair	1	7.0E05
Microwave Link	50,000	Repair	1	1.0E06
10-Telephone Companies				
Tel. PBX	1,300,000	Critical	1	7.0E05
11-Radio/TV				
Studio Equip.	15,000	Disruptive	1	1.6E07
Transformer and Transmitter	0	Disruptive	1	1.0E06
Mobile Mini Cam.	50,000	Repair	3	1.6E07
Control Room	5,000	Critical	1	3.0E05
12-Gas & Electric Utilities				
Switching Control Rm	100,000	Disruptive	1	3.0E05
Billing Computer	100,000	Repair	1	4.9E09*
13-General Merchandise Retailers				
POS Terminal	2,000	Disruptive	15	1.0E07
Computer	15,000	Disruptive	1	4.9E09*
14-Retail Grocers				
Registers	200	Disruptive	12	1.0E07
Computer	10,000	Disruptive	1	4.9E09
15-Financial & Insurance				
Computer	100,000	Disruptive	1	4.9E09*
Gen. Ofc. Equip.	1,300***	Disruptive	1***	5.0E05
16-Computer Services				
Computer	100,000	Critical	1	4.9E09*
Gen. Ofc. Equipment	1,300***	Disruptive	1***	5.0E05

* Incorporates Computer Room Transfer Function.

*** 10 Typewriters, 20 Calculators, 2 Xerox Machines.

TABLE G-5 (Cont'd.)

<u>Facility and Equipment Type</u>	<u>Repair Cost per Unit</u>	<u>Level of Failure</u>	<u>Number of Equipment</u>	<u>Mean Dosage for Failure</u>
17-Computer Services				
Computer	100,000	Critical	1	4.9E02*
Gen. Ofc. Equipment	1,300***	Disruptive	1***	5.0E05
18-Electronic R&D, Universities, Colleges				
Instruments	500	Repair	100	5.9E05
19-Hospitals				
PBX	25,000	Repair	1	7.0E05
Generator	20,000	Repair	1	9.8E05
X-Ray	20,000	Repair	6	1.0E06
Gen. Instr.	750	Repair	200	5.9E05
20-Airplanes				
APU	3,750	Repair	1	1.0E07
Cabin Inst.	7,500	Repair	1	3.0E05
Avionics	60,000	Disruptive	1	1.0E06
21-Control Tower at Airport				
Computer	25,000	Repair	1	4.9E09
Radios	10,000	Repair	1	1.0E06
Consoles	35,000	Repair	1	7.0E05
CRT	10,000	Repair	1	1.5E06
22-Terminal at Airport				
X-Ray	450	Repair	14	1.0E06
TTY	300	Repair	89	7.0E05
Printers	150	Repair	30	3.0E06
CRTS	30	Repair	48	1.6E07
23-ASR-Field Radar at Airport				
ASR	30,000	Repair	1	1.5E06

* Incorporates Computer Room Transfer Function.

*** 10 Typewriters, 20 Calculators, 2 Xerox Machines.

TABLE G-5 (Cont'd.)

<u>Facility and Equipment Type</u>	<u>Repair Cost per Unit</u>	<u>Level of Failure</u>	<u>Number of Equipment</u>	<u>Mean Dosage for Failure</u>
24-LOC at Airport LOC	15,000	Repair	3	7.6E06
25-VOR at Airport VOR	7,500	Repair	1	7.6E06

TABLE G-6
ECONOMIC DATA SOURCES

Facility Category	Sources of Data for Numbers of Establishments	Source of Data for Revenue (or Value Added)
1	1972 U.S. Census of Population	N/A
2	Estimated as Proportion of Households	N/A
3	American Bureau of Shipping, 1977 Record	N/A
4	Estimated as Proportion of Households	N/A
5	Allocated to Major Metropolitan CBD	N/A
6	American Public Transit Association, <u>1976 Transit Operating Report</u>	N/A
7	U.S. Census Bureau, 1975 County Business Patterns	1972 Census of Manufacturing
8	"	"
9	Allocated to Major Metropolitan CBD	N/A
10	U.S. Census Bureau, 1975 County Business Patterns	Robert Morris Associates 1976 <u>Annual Statement Studies</u>
11	"	"
12	"	<u>Annual Report</u> , Edison Electric Institute
		<u>Annual Report</u> , Am. Gas Association
13	"	1972 Census of Retail Trade
14	"	"
15	"	Federal Reserve, Board of Governors
16	"	1972 Census of Selected Services
17	"	"
18	"	N/A
19	"	N/A
20	Federal Aviation Administration, Form 5010-1, Airport Master Record	Civil Aeronautics Board, <u>Aircraft Operating Cost and Performance Report</u> , July '78
21	"	N/A
22	"	N/A
23	"	N/A
24	"	N/A
25	"	N/A

The revenues for the following five categories were estimated based on national data, and thus the revenue estimates are identical for all cities.

<u>CATEGORY</u>	<u>REVENUE</u>
10 - Telephone Company Branch Office	\$12,664
11 - Radio, Television, Communication Service	15,224
12 - Gas and Electric Utilities	48,909
15 - Financial and Insurance Institutions	11,000
20 - Airplanes at Airports	15,000

The revenues for the remaining categories were estimated on the basis of census data for the major Standard Metropolitan Statistical Area (SMSA) for each airport. These are presented in Table G-7.

The SIC codes corresponding to each category were as follows:

Category 7: SIC 3568
 " 8: SIC 3573
 " 13: SIC 531, 56, 57, 59
 " 14: SIC 541
 " 16: SIC 73
 " 17: SIC 737

(Dollar Revenue Per Day)

TABLE G-7

AVERAGE FACILITY REVENUES IN DOLLARS/DAY

CITY	C A T E G O R Y*					
	7	8	13	14	16	17
Phoenix	26,160	16,500	1,182	4,323	478	3,007
Los Angeles	26,160	25,080	1,237	6,120	619	2,676
San Francisco	26,160	25,980	1,363	4,302	657	3,663
Denver	26,160	16,500	1,194	6,864	424	1,726
D.C.	26,160	3,660	1,797	6,105	753	386
Atlanta	26,160	16,500	1,509	2,722	730	2,337
Honolulu	26,160	16,500	1,279	5,364	429	939
Chicago	12,060	16,500	1,835	4,429	1,260	1,950
New Orleans	6,540	10,125	1,560	3,472	756	2,118
Detroit	37,740	17,940	1,690	4,297	1,146	2,155
Minneapolis	7,980	16,500	1,464	4,689	705	1,884
Kansas City	26,160	16,500	1,242	4,966	667	1,898
St. Louis	26,160	16,500	1,317	427	760	4,908
Las Vegas	26,160	16,500	1,405	6,118	639	1,410
Newark	26,160	18,660	1,488	4,926	651	2,608
Kennedy	26,160	930	1,383	3,024	1,707	3,006
Laguardia	26,160	930	1,383	3,024	1,707	3,006
Cleveland	10,560	16,500	1,438	3,834	826	1,633
Philadelphia	26,160	18,540	1,350	3,340	718	2,715
Pittsburgh	26,160	13,080	1,299	3,033	662	1,872
Seattle	26,160	16,500	1,221	444	421	1,914
Miami	26,160	16,500	1,227	3,771	456	1,677
Tampa	26,160	16,500	1,182	2,785	465	1,504
Dallas	26,160	16,500	1,044	3,036	609	3,234
Houston	26,160	16,500	1,318	2,899	720	3,261
Boston	26,160	16,500	2,340	7,260	948	3,270

* See Table G-5.

H. STATISTICAL ANALYSIS OF CONFIDENCE BOUNDS

H.1 EFFECT OF ECONOMIC LOSS VARIABILITY

Although economic loss data were assumed constant within facility categories, the variability of these losses would introduce only a small amount of additional variability in the risk profile. To illustrate this principle, suppose we simplify the model and assume that the total dollar loss in an accident is

$$\text{Loss} = X \sum_{L=1}^N L_i$$

where N = Number of losses

L_i = The amount of dollar loss i

and L_i and N are both random. It follows (see Chapter 11, reference [4]) that:

$$EX = U_N U_L$$

$$\sigma_X^2 = \text{Var } X = U_N^2 \sigma_L^2 + U_L^2 \sigma_N^2 \quad (\text{H-1})$$

where

EX = Expected loss

U_N = Expected N

U_L = Expected L_i

σ_L^2 = Var L_i

σ_N^2 = Var N

In our analysis, we assumed that

$$\sigma_L = 0$$

Supposing, for example, that

$$U_L = \$1000$$

and noting that for the 1993 conditional risk profile,

$$EX = 131,000$$

$$\sigma_X = 417,000$$

we can solve (H-1) to obtain

$$U_N = 131$$

$$\sigma_N = 417$$

If we then assume that there is a variability of L_i of 3 times the mean, or,

$$\sigma_L = 3000$$

we recompute σ_X from (H-1) and obtain

$$\begin{aligned}\sigma_X &= 131(3000)^2 + (1000)^2 (417)^2 \\ &= 418,400\end{aligned}$$

This example shows that a large variability in individual dollar losses does not greatly affect the variability of the total dollar loss.

H.2 DERIVATION OF STATISTICAL BOUNDS ON THE CONDITIONAL PROFILE

To construct a confidence bound for a simulated empirical conditional profile, we considered two approaches: the preferred approach made use of Poisson and binomial confidence bounds for observed frequencies, and gave better results than the approach using Kolmogorov-Smirnoff and Anderson-Darling confidence bounds for empirically generated probability distributions. (See Chapter 11, reference [5].)

One of the problems in utilizing any of these methods is that our sample was a stratified sample of 300 iterations per city where some cities represented larger conditional probabilities than others. Consider the following procedure to compute a confidence bound for the national conditional probability of an accident exceeding \$9 million. The bound is based on the Poisson distribution for observing frequencies of events.

Suppose the conditional probability of an accident at city i given an accident nationally is:

$$F_i = P(ACC_i)/P(ACC)$$

Suppose that the conditional probability of an accident at city i exceeding \$9 million is X_i . Then the conditional probability that an accident occurring somewhere in the nation exceeds \$9 million is

$$\text{Probability} = y = \sum F_i X_i$$

To determine a confidence bound for y , we need to know the appropriate values for the variables X_i so that the observed occurrence of no losses exceeding \$9 million dollars is the 5% lower tail point of the Poisson distribution.

This tail point would be obtained from a Poisson distribution with parameter 3. Thus, if 3 events are expected, a value of 0 would be the 5% lower tail point. If there are 300 samples per city, and city i represents a probability of occurrence (of a loss exceeding \$9 million) per sample of X_i , then the expected number of occurrences nationally is $300 \sum X_i$.

By equating this expectation to 3, we obtain the equation

$$\sum X_i = \frac{1}{100}$$

The confidence bound is thus

$$y = \sum F_i X_i$$

where $\sum X_i = \frac{1}{100}$

for some feasible combination of X_i . By inspecting this system of equations, it is seen that the worst (largest) possible bound is obtained when $X_i = .01$ for the city with the highest value of F_i . Thus,

$$y = (\max F_i)(.01)$$

This city is Chicago whose F_i value is .128 and thus the 95% upper confidence bound is 1.28×10^{-3} .

This bound is equal to the bound obtained by considering no observations in 2350 independent national trials. In other words, since only 300 trials were drawn for a segment representing 12.8% of the possibilities, we are drawing the equivalent of

$$\frac{300}{.128} = 2350$$

for 100% of the possibilities.

We utilized the same methodology for the entire curve. For low probability events, we developed Poisson bounds. For medium and high probability events, we developed bounds based on frequencies of the binomial distribution. For example, for the dollar loss corresponding to a frequency of 50% of 2350 samples, we determined the upper and lower binomial parameters corresponding to such a 50% frequency. Our bounds therefore represent a combination of individual bounds on each observed point. These bounds were tighter than the Kolmogorov-Smirnoff or Anderson-Darling confidence bounds for 2350 samples, which represent a confidence curve for the maximum deviation statistics.